The Utility of Microfossils in Geoarchaeology: A Case Study from Lake Simcoe, Ontario and Methodological Considerations

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Abstract

Eutrophication has been an issue in Lake Simcoe since the 1970s, stressing aquatic wildlife, notably economically-important cold water fish. Non-pollen palynomorphs (NPP) are more sensitive proxies of water quality than sedimentary phosphorus, and have a higher fossilization potential than mineralized microfossils like diatoms, although some, notably desmids, were shown to be sensitive to acetolysis. Algal palynomorphs record cultural eutrophication since European settlement at all three sites in a north-south transect (particularly at the southern site Cook's Bay) and similar NPP assemblages record eutrophication below the *Ambrosia* (ragweed) rise in cores from the main basin and Smith's Bay. This event has been attributed to the Wendat (Huron) occupation of Wendake (Huronia) that ended in the mid-seventeenth century, an attribution supported the by increases in micro-charcoal, likely from controlled fires and the presence of palynomorphs associated with agriculture.

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Table of Contents

Chapter 1: Introduction 1

1.1 Study Overview & Purpose 1

1.2 Paleolimnology & Indicators of Cultural Eutrophication 3

1.3 Palynology 4

1.3.1 Primary Producers: Algae 9

1.3.2 Consumers: Protozoans and Invertebrate Animals 12

1.4 Mineralised Microfossils 14

1.5 Microfossils & Archaeology 16

1.5.1 Native American Settlement in Ontario 16

1.6 Sources 20

Chapter 2: The Effect of Acetolysis on Desmids 30

2.1 Introduction 30

2.2 Methods 34

2.2.1 Palynological Processing 34

2.2.2 Loss-on-Ignition (LOI) and Geochemical Analysis 35

2.3 Results 35

2.4 Discussion 38

2.5 Conclusion 41

2.6 Sources..... 42

Chapter 3: Non-Pollen Palynomorph Evidence of Human Impact on Lake Simcoe: Applications for Water Resource Management..... 48

3.1 Introduction..... 48

3.1.1 Lake Simcoe..... 52

3.1.2 NPP as Tools in the Management of Water Quality in Lake Simcoe..... 54

3.2 This Study..... 60

3.3 Methods..... 61

3.3.1 Coring & Subsampling..... 61

3.3.2 Geochemical Analysis..... 61

3.3.3 Palynological Processing..... 61

3.4 Results..... 62

3.4.1 Algal palynomorphs from core SB-1, Smith's Bay..... 62

3.4.2 Detailed Algal Palynomorph Data from Core CB-1, Cook's Bay..... 65

3.5 Discussion..... 67

3.6 Conclusions..... 72

3.7 Sources..... 73

Chapter 4: Palynological Record of Pre-European Anthropogenic Impact on Lake Simcoe..... 84

4.1 Introduction..... 84

4.1.1 Paleolimnological Evidence of the Wendat in Southern Ontario 87

4.1.2 Palynological Evidence of Anthropogenic Impact on Lake Simcoe 91

4.2 Methods 95

4.2.1 Coring 95

4.2.2 Palynological Processing 95

4.3 Results 96

4.4 Discussion 99

4.5 Conclusion 103

4.6 Sources 104

Chapter 5: Conclusion 109

5.1 Future Research 112

5.2 Sources 115

Appendix A: Smith's Bay Microfossil Data

Appendix B: SB-2 Core Description & Nutrient & Heavy Metal Lab Results

Appendix C: Lake Simcoe Bathymetry & Circulation Models

Appendix D: Upper Canada Historical Maps

List of Tables

		Page
Chapter 3		
Table 3.1	Ecology of desmids, *Pediastrum*, *Botryococcus* & dinoflagellate cysts	57
Table 3.2	Algal palynomorphs & testate amoebae in the upper 10 cm of Lake Simcoe	69
Table 3.3	Algal palynomorphs & testate amoebae in the upper 10 cm and below the ragweed rise of Lake Simcoe	69
Chapter 4		
Table 4.1	The Wendat Confederacy	85

List of Figures

		Page
Chapter 1		
Figure 1.1	Pollen succession from Hams Lake	6
Figure 1.2	Pollen & algal palynomorphs from Second Lake	8
Figure 1.3	Diatom assemblage from Crawford Lake	18
Figure 1.4	Pollen & NPP assemblage from Crawford Lake	18
Figure 1.5	Dinoflagellate cyst assemblage from Crawford Lake	19
Chapter 2		
Figure 2.1	Lake Simcoe	33
Figure 2.2	Unacetolysed desmid assemblage from core SB-1	36
Figure 2.3	LOI & Geochemical analysis from core SB-2	37
Figure 2.4	Comparison of pre- & post-acetolysis desmid assemblage from core SB-1	38
Figure 2.5	Desmid, *Pediastrum* & dinoflagellate cyst assemblage from core SB-1	39

Chapter 3

Figure 3.1	Chironomid- & diatom-based paleolimnological analysis from the main basin, Lake Simcoe	50
Figure 3.2	NPP assemblage & diversity from core L0S7 PC5	51
Figure 3.3	Lake Simcoe biomass	54
Figure 3.4	Geochemical analysis from core CB-1	56
Figure 3.5	NPP assemblage from core CB-1	58
Figure 3.6	NPP & testate amoebae assemblage from core L0S7 PC5	59
Figure 3.7	Geochemical analysis from core SB-1	60
Figure 3.8	Desmid assemblage from core SB-1	63
Figure 3.9	*Pediastrum* assemblage from core SB-1	64
Figure 3.10	Pollen assemblage from core SB-1	65
Figure 3.11	Speciated NPP assemblage from core CB-1	66
Figure 3.12	Algal palynomorphs, diatoms & chlorophyll *a* from the main basin, Lake Simcoe	71

Chapter 4

Figure 4.1	Pre-contact & documented Iroquoian territories	85
Figure 4.2	Distribution of Wendat villages in the early seventeenth century	86
Figure 4.3	Microfossil assemblage from Crawford Lake	88
Figure 4.4	Geochemical analysis from Crawford Lake	89
Figure 4.5	Microfossil assemblage from Second Lake	90
Figure 4.6	Microfossil assemblage from Honey Harbour	91
Figure 4.7	NPP & testate amoebae assemblage from core SB-1	93
Figure 4.8	Geochemical analysis from cores SB-2 & CB-1	94
Figure 4.9	Micro-charcoal, fungal spore/hyphae & NAP assemblage from core SB-2	96
Figure 4.10	Fungal spore/hyphae & NAP assemblage from core SB-1	97
Figure 4.11	Desmid ecology from core SB-1	98

Figure 4.12 Desmid ecology from core L0S7 PC5 99
Figure 4.13 NAP assemblage from core L0S7 PC5 100
Figure 4.14 Algal palynomorph assemblage from core L0S7 PC5 102

List of Plates

Page

Chapter 1

Plate 1.1 Representative algal palynomorphs from Lake Simcoe 12
Plate 1.2 Loricae of tintinnid ciliate & rotifer 13
Plate 1.3 Mineralized microfossils in lacustrine sediments 15

Chapter 2

Plate 2.1 Common desmids from Lake Simcoe 32
Plate 2.2 *Pediastrum* coenobia, pre- & post-acetolysis 41

Chapter 4

Plate 4.1 Select NAP and fungal spores from core SB-1 101

List of Abbreviations

NPP	Non-pollen palynomorph
NAP	Non-arboreal pollen
AP	Arboreal pollen
DO	Dissolved oxygen
BOD	Biological/Biochemical oxygen demand
TP	Total phosphorus
NO_2	Nitrite
NO_3	Nitrate
Al	Aluminum
Fe	Iron
K	Potassium
Na	Sodium
Ti	Titanium
HCL	Hydrochloric acid
HF	Hydroflouric acid
^{14}C	Carbon 14
^{210}Pb	Lead 210
°C	Degrees Celsius
pH	Measure of the –log (H+)
SDI	Shannon Diversity Index
LOI	Loss on ignition
Eu	Eutrophic
Meso	Mesotrophic
Oligo	Oligotrophic
sp.	A single, unspecified species within a genus
spp.	Many species within a genus

YBP	Years before present
Cal. BP	Calibrated years before present
Ka	Thousand years
CE	synonymous with AD
AD	Anno Domini, synonymous with CE
BC	Before Christ, synonymous with BCE (Before Common Era)
WWII	World War II
~	Approximately
ca.	Approximately
M	Metre
m^2	Square meter
Cm	Centimetre
Km	Kilometre
km^2	Square kilometre
mg/kg	Milligrams per kilogram
mL	Millilitre
µm	Micrometre
LSEMS	Lake Simcoe Environmental Management Strategy
LSRCA	Lake Simcoe Regional Conservation Authority
LSPP	Lake Simcoe Protection Plan
MOE / MOECC	Ontario Ministry of the Environment
CB-1	Cook's Bay sediment core
SB-1	Smith's Bay sediment core
SB-2	Smith's Bay sediment core (replicate of SB-1)
L0S7 PC5	main basin sediment core

Chapter 1: Introduction

While the field of geoarchaeology is well established, being taught at several universities and having its own academic journal (*Geoarchaeology*), the discipline lacks definition, and when definition is given, it is usually broad. For example Pollard (1999) defines geoarchaeology as "application of the geosciences to solve research problems in archaeology", though he notes clearly that there is controversy in terms of what the field encompasses and how it is different geographically (i.e., in Europe vs. North America). Jones (2013), who uses geoarchaeology to mean 'archaeological geology' (geological research by geologists for archaeology vs. archaeologists employing earth science concepts), asks if some of the research being done actually falls under geoarchaeology and if the term needs to be redefined as it is used to cover something in a larger interdisciplinary space. This controversy aside, earth science (e.g., geology, stratigraphy, sedimentology, geochemistry, mineralogy, paleontology and paleoecology) is an important component in archaeological research. Colin Renfrew stated in 1976 that every archaeological problem starts with geoarchaeology (Pollard, 1999), and Goldberg & Macphail state in their book '*Practical and Theoretical Geoarchaeology*' (2006) that "geoarchaeology provides the ultimate context for all aspects of archaeology from understanding the position of a site in a landscape setting to a comprehension of the context of individual finds and features". For the purpose of this document, geoarchaeology will be defined following Pollard (1999).

1.1 Study Overview & Purpose

The purpose of this thesis is to investigate the sensitivity of microfossils to human activities, which can be related to historical and prehistoric events. The remainder of this chapter will provide basic information about paleolimnology, organic-walled and mineralized microfossils, vegetation response to land disturbance, palynomorphs associated with cultivars, and the response of fossilizable algae and herbivores to cultural eutrophication. **Chapter 2** (Riddick et al. 2016) investigates the impact of acetolysis (a common oxidizing method employed by palynologists) on the non-pollen palynomorph (NPP) record. **Chapters 3** and **4** examine the response of Lake Simcoe to anthropogenic

disturbance in its watershed, assessed using microfossil and geochemical proxies of siltation and eutrophication (see details below). **Chapter 5** will summarize and conclude this document with suggestions for application to other studies, notably the Burgaz Harbors Project. Data generated, compiled and analyzed for use in the aforementioned chapters is provided in the **Appendix.**

Chapter 3 compares NPP data from Smith's Bay with that from two other sites (the main basin of Lake Simcoe and Cook's Bay), demonstrating the geographic response of Lake Simcoe to human settlement in its watershed and the sensitivity of NPP to different intensities and types of human activity. Of particular interest is a zone around 60 cm in core SB-1 which has similar microfossil characteristics as sediments associated with the *Ambrosia* (ragweed) rise, indicative of early-European land clearing and settlement during the mid-nineteenth century (Chittenden, 1990). Additionally, elemental analysis from core SB-2, initially presented in **Chapter 2** (Riddick et al. 2016), identified an increase in nutrients and heavy metals around 60 cm that is comparable to that in the lower part of the ragweed zone.

Although **Chapter 2** (Riddick et al. 2016) and **Chapter 3** tentatively attribute evidence of pre-European eutrophication and siltation to the Wendat/ Huron, the results of a detailed investigation are reported in **Chapter 4**. Analysis of pollen, focusing on non-arboreal pollen (NAP) and fungal spores (notably the cultivar pathogens) was completed on acetolysed samples throughout cores SB-1 and SB-2 to assess land disturbance and agricultural activity. Because it destroys most of the amorphous organic matter that is common in sediments, acetolysis makes oxidation-resistant palynomorphs like pollen easier to count, as they are not obscured. On the other hand, it destroys oxidation-sensitive palynomorphs, notably half-cells of desmids that are abundant in sediments from Lake Simcoe and are also sensitive proxies of anthropogenic impact (**Chapter 2**, Riddick et al. 2016). The NAP and fungal spore record, augmented by micro-charcoal analysis, provide insight into the degree and type of land disturbance, which combined with findings about water quality from **Chapter 3** and the regional historical and archeological record, aid in the **Chapter 4** investigation of pre-European/ Native land clearing and settlement.

1.2 Paleolimnology & Indicators of Cultural Eutrophication

Paleolimnology is the study of aquatic systems, usually freshwater lakes, using physical, chemical and biological proxies preserved in sediments. These proxies can be used to reconstruct past environmental conditions and establish base-line conditions (i.e., before human impact) (Smol, 2001). This provides insights into limnological conditions before modern monitoring records. Transfer functions have been developed for several microfossil groups, providing quantitative reconstructions of paleoenvironmental parameters like temperature, precipitation, pH, and nutrient content (e.g., Bartlein & Whitlock, 1993; Patterson et al. 2012).

Water quality issues were first documented in Lake Simcoe in the 1970s, notably algal blooms associated with total phosphorous (TP) loading. Phosphorus is normally the limiting nutrient for primary production in freshwater ecosystems (Schindler, 1974). The pre-European TP load into Lake Simcoe was ~32 tonnes/ year and has increased to ~72 tonnes/ year (LSRCA 2009). Cultural eutrophication (nutrient loading into aquatic environments from anthropogenic sources/ activities) often results in low dissolved oxygen (DO) concentrations due to increased biochemical/ biological oxygen demand (BOD). Low DO in Lake Simcoe has negatively affected the lake's cold water fish and thus the economy of the region. Additionally, blooms of algae and other organisms suspended in the water column (phyto- and zooplankton) cause a decrease in light penetration which is detrimental to benthic photosynthetic organisms living lower in the water column and on the lakebed (Smol, 2008). Since the 1980s, programs have been in place to reduce TP loading and overall conditions are improving, but DO concentrations are still considered too low (MOECC, 2016). Cultural eutrophication in Lake Simcoe is discussed further in **Chapter 3**.

To assess and investigate eutrophication, many researchers measure nutrients (e.g., phosphorus) and biomass (Carlson, 1977; Torbick et al. 2008). Biomass and nutrient measurements in the water column can provide useful information about a system at the time of collection, and can be combined with other 'snapshots' (e.g., flora/ fauna and metals/ pollutants), to infer more about the system's overall status. Measurements of sedimentary nutrients like phosphorus can extend records back before modern

monitoring, but the use of sedimentary phosphorus concentrations to infer the history of nutrient flux (Hiriart-Baer et al. 2011) has been called into question (Ginn et al. 2012). The state of phosphorus must be considered (i.e., is it bioavailable?). Meng et al. (2014), who conducted a study on phosphorus in surface sediments in the Changjiang Estuary and adjacent East China Sea inner shelf, identified six types of sedimentary phosphorus and the average contribution from each: exchangeable (2.5%), authigenic (5.5%), detrital (55.6%), organic (16.1%), refractory (17.8%) and iron-bound (2.5%). Collectively these sources comprise the TP component in a system. According to Meng et al. (2014), exchangeable, organic and iron-bound phosphorus can easily be released through physical, chemical and/ or biological reactions and therefore are potentially bioavailable. Bioavailable phosphorus in these surface sediments accounted for an average of 21.2% of TP.

The fossil remains of aquatic organisms provide an alternative that can be combined with traditional proxies, such as sedimentary nutrient analysis. Aquatic organisms are sensitive to nutrient status of the water body and their fossil remains are useful biomonitors, not only of nutrient loading, but also of siltation/ turbidity and heavy metal flux to the water body resulting from land clearing for agriculture, urbanization and industrialization (e.g., Hall & Smol, 1996; Smol, 2010; Haas, 2010: Mudie et al. 2011; McCarthy et al. 2011; Danesh et al. 2013; McCarthy & Krueger, 2013; Drljepan et al. 2014). Time series analysis of environmental data recorded by microfossils illustrates the response of lakes to environmental stresses over time that synoptic measurements of water quality cannot capture (Smol, 2010). Danesh et al. (2013) and Riddick et al. (2016) analysed metals and nutrients (including TP) in conjunction with microfossils in embayments of Lake Simcoe. TP includes types of sedimentary phosphorus that are not bioavailable, however the aquatic organisms producing various microfossils respond only to the bioavailable fractions. Without the microfossil analysis, the extent of cultural eutrophication in these studies cannot be fully or accurately assessed.

1.3 Palynology

Palynology is the study of acid-resistant organic-walled microfossils composed of readily fossilizable materials such as dinosporin, sporopollenin, chitin, algaenan, or pseudochitin

(Traverse, 1988; Benton & Harper, 1997) that are produced by organisms from all kingdoms of life either as skeletal material (e.g., chironomid head capsules or lorica of ciliates or rotifers, plant stomata, desmid half-cells, chlorophyte colonies) or as part of their life cycle, usually involved with reproduction (e.g., pollen and embryophyte spores, fungal spores, or algal cysts or zygospores). While this field is sometimes (erroneously) considered synonymous with the study of pollen (and embryophyte spores), there are a variety of useful non-pollen palynomorphs (NPP). Palynomorphs have proven to be useful tools for dating sediments, hydrocarbon exploration and in environmental studies (Lipps, 1981; Traverse, 1988).

Pollen and Spores: Embryophytes reproduce by means of pollen or spores that are composed of a highly resistant organic compound called sporopollenin. Transport of these pollen and spores is primarily by wind (anemophilous), but some require animal vectors (e.g., insects, birds, bats). Most anemophilous pollen and spores do not achieve their reproductive purpose and are deposited on the landscape and in water bodies, where they eventually settle through the water column and are preserved in the sediment. Atmospheric turbulence results in a uniform mixture of pollen and spores (suspended in the atmosphere) giving rise to 'pollen rain' over a given region. This makes pollen and spore analysis in sediment samples an excellent proxy for the study of terrestrial environmental change over time (McAndrews, 1981, 1994; Bennett & Willis, 2001).

Paleolimnologists can study the distribution of pollen and spores in sediment cores, determining upland vegetation assemblage. Vegetation changes through time/ up-core can result from climate change (e.g., glaciation) or natural (e.g., fire and disease) and anthropogenic land disturbance. Furthermore, chronological control for sediment cores can be achieved through comparison with other, nearby, well dated cores (Bennett & Willis, 2001). McAndrews (1981, 1994) established pollen zones, recording regional vegetation change following deglaciation, allowing for correlation between sites in southern Ontario (**Figure 1.1**).

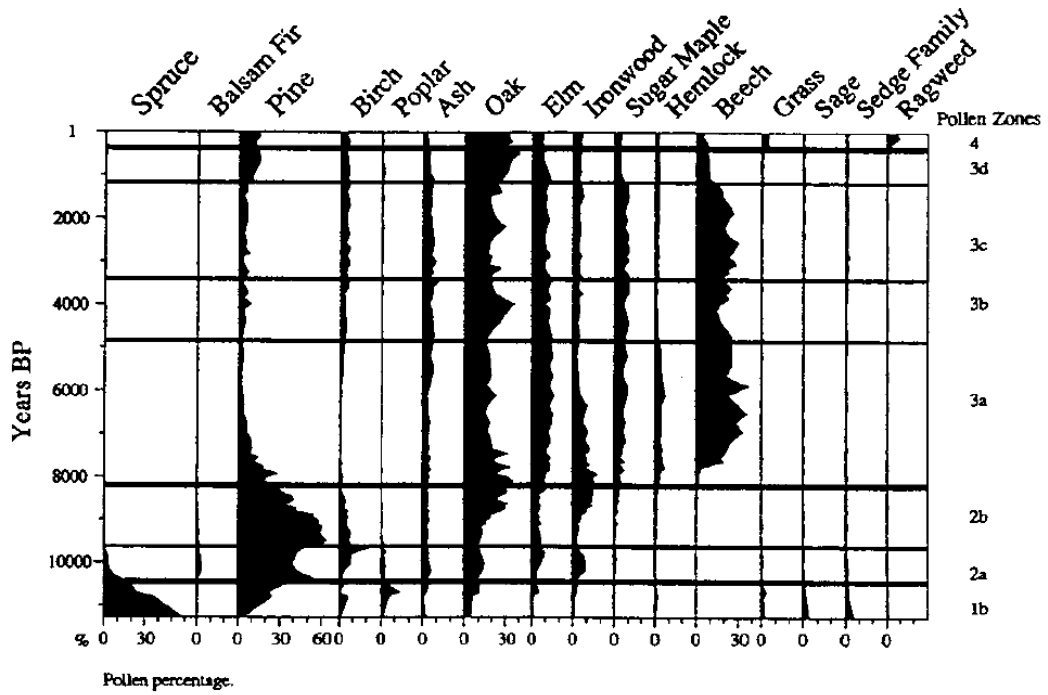

Figure 1.1: Pollen succession from Hams Lake illustrating postglacial vegetation succession associated with regional climate change (McAndrews, 1994). The dominance of spruce with relatively high abundances of non-arboreal pollen (NAP) records the establishment of spruce woodland/ forest-tundra immediately following deglaciation. Pine pollen dominates pollen zone 2, together with xeric hardwoods like oak, elm and ironwood, recording drought conditions in the Great Lakes region during the early Holocene (McCarthy & McAndrews, 2012). An increase in beech, hemlock and sugar maple abundances marks the establishment of pollen zone 3, recording warm, moist conditions that allowed the establishment of the mixed forest that characterised the Great Lakes region until anthropogenic land disturbance produced an increase in ragweed and other NAP, establishing zone 4.

Of particular note is pollen zone 4, which is characterized by an increase in ragweed and other NAP (**Figure 1.1**). This is also referred to as the ragweed rise, which is attributed to settlement and land clearing activities by European settlers (McAndrews, 1994). Although, in 1615, Samuel de Champlain observed that the landscape in Huronia "was cleared, with many open fields and meadows…" (Heidenreich, 1971), ragweed pollen did not rise sharply in abundance until ca. 1840, even in Wye Marsh, the site of Ste. Marie-Among-the-Hurons (Chittenden, 1990). Similarly, in Awenda Provincial Park (specifically Second Lake and Lake Gignac), Burden et al. (1986) found an increase in ragweed and other NAP associated with Euro-Canadian logging and farming in the latter half of the nineteenth century. A much more muted vegetation response, in the lower part of pollen subzone 3d, was associated with the Wendat land clearing and agriculture. Burden et al. (1986) noted that there were three Wendat villages within 1 km of Second Lake and one known village on the western end of Lake Gignac, showing that this

vegetation response occurred in populous areas. **Figure 1.2** illustrates the pollen record for two cores from Second Lake, together with the abundances of *Pediastrum* and dinoflagellate cysts attributed to *Peridinium wisconsinense* and *P. willei*. In the lower part of zone 3d, algal abundances (notably *P. wisconsinense*) decrease, with *Pediastrum* abundance increasing slightly. In Gignac Lake, *P. willei* increases as *P. wisconsinense* decreases in pollen zone 3d. In the upper part of zone 3d, both *Pediastrum* and *P. wisconsinense* abundances decrease.

Although the transition to pollen zone 4 is clearly recorded by a decrease in oak, birch and pine and increase in ragweed pollen, there is little indication of human impact in the pollen record of the lower part of zone 3d (**Figure 1.2**). This reflects the much more extensive land-clearing associated with Euro-Canadian settlement than with Wendat villages. The response of algal palynomorphs to both phases of human impact is more analogous, the lower part of zone 3d appearing similar to zone 4 and very different from intermediate or pre-settlement zones. This is discussed further in **Chapter 4**.

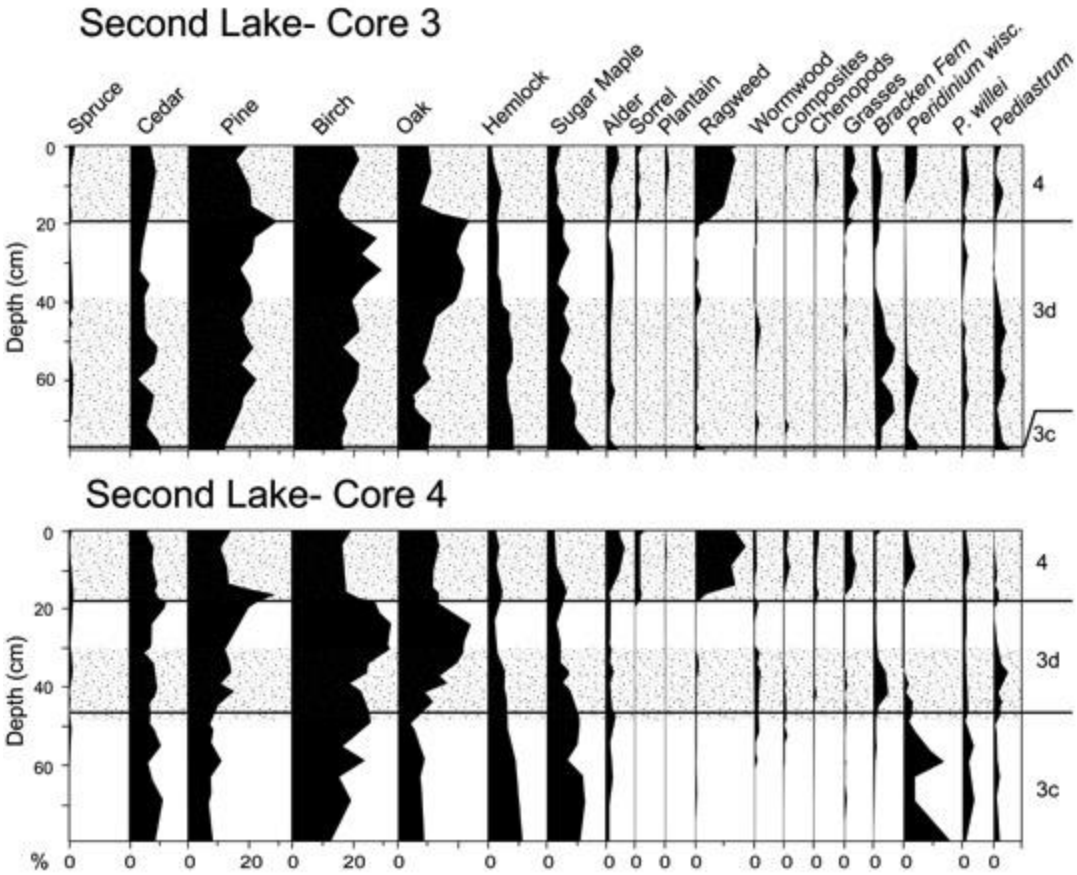

Figure 1.2: Pollen and algal palynomorph abundance from Second Lake in Awenda Provincial Park (modified from McCarthy et al. 2011, after Burden et al. 1986) highlight two periods of human occupation (Euro-Canadian in zone 4 and Wendat in the lower half of zone 3d). While the change in the pollen record, specifically the increase in ragweed pollen indicates Euro-Canadian land clearing, the pollen response to Wendat land clearing is comparatively slight. Similarities in the abundances of *Pediastrum*, *Peridinium wisconsinense* and *P. willei* in the lower part of zone 3d and zone 4 clearly record eutrophication. With algal palynomorphs identifying the presence of the Wendat in the lower part of zone 3d, subtle changes in the pollen assemblage (e.g., increases in some NAP) can be associated with human impact.

Non-pollen Palynomorphs (NPP): Many other acid-resistant microfossils survive palynological maceration in addition to pollen and spores. These NPP represent all kingdoms of life (e.g., remains of aquatic invertebrate animals, algae, bacteria, fungi and protozoans) (van Geel, 2001). While oxidizing techniques such as acetolysis are common when processing for pollen, they can destroy some NPP, notably half-cells of desmids (Riddick et al. 2016). NPP have been found to be excellent proxies of past environmental conditions and human impact due to their varied environmental preferences (van Geel, 2001; Haas, 2010). NPP that are common in sediments from Lake Simcoe are described below in further detail.

1.3.1 Primary Producers: Algae

Algal microfossils are common in paleolimnological studies, particularly diatoms which have been the subject of environmental work since the late-nineteenth and early-twentieth centuries (Kolkwitz & Marsson, 1908; Nipkow, 1920). Diatoms, which are discussed further in **Section 1.4**, are not considered palynomorphs as they are not resistant to hydrofluoric acid (HF), which is common in palynological processing. However, there are a number of algal palynomorphs (e.g., desmid half-cells, *Pediastrum* coenobia, *Botryococcus* colonies, and dinoflagellate cysts), that are the focus of **Chapters 2-4**. Most of these are green algae (Kingdom: Plantae), the exception being dinoflagellates (Kingdom: Chromista).

<u>Desmids:</u>

- Phylum: Charophyta, Class: Zygnematophyceae, Order: Desmidiales, Family: Desmidiaceae (**Plate 1.1**).

Desmids are conjugated green algae, many of which are benthic (bottom dwelling) and live in meso-oligotrophic freshwater environments, although some are planktonic and prefer eutrophic conditions (notably most species of *Staurastrum*). They have been reported from sediments as old as Devonian (Dana, 1863), but are common since the Late Cretaceous (Waggoner, 1994; Schwab et al. 2011). They have been used as proxies of trophic status (Coesel, 1983) and nutrient loading (Gerrath, 2003; Garner, 2015). Gerrath (2003) notes that they are especially abundant and diverse in the Canadian Shield and Riddick et al. (2016) demonstrated that their half-cells can be abundant in palynological preparations as long as samples are not acetolysed. Three common genera of desmids are found in sediments from Lake Simcoe:

1. *Cosmarium:* have semi-circular half-cells and lack ornamentation (van den Hoek et al. 1995). They can be found in a range of environments from oligotrophic to eutrophic (van den Hoek et al. 1995; Gerrath, 2003).
2. *Euastrum:* have semi-cells with many indentations, may be confused with *Cosmarium*. They are usually found in oligotrophic environments (Gerrath, 2003).

3. *Staurastrum:* these vary in shape, have ornamentation, and are typically planktonic. Most prefer eutrophic waters and can be useful for analyzing nutrient loading (Gerrath, 2003).

Pediastrum:

- Phylum: Chlorophyta, Class: Chlorophyceae, Order: Sphaeropleales, Family: Hydrodictyaceae, Genus: *Pediastrum* (**Plate 1.1**).

Pediastrum are typically 'star-shaped' colonial green algae that live in freshwater environments. The earliest (compact/ unornamented coenobia) are known in lacustrine sediments from the Early Cretaceous (Batten, 1996). These organisms are usually periphytic or planktonic and primarily prefer eutrophic waters (van den Hoek et al. 1995; Shubert, 2003). The level of ornamentation determines their position in the water column (Padisak et al. 2003). Komarek & Jankovska (2001) have noted the usefulness of *Pediastrum* as paleoecological indicators; Cronberg (1982) specifically noting how the responses of various species can be used as an indicator of trophic status. Their resistant and distinct coenobia (colonies) are frequently mentioned by palynologists studying freshwater sediments (e.g., Burden et al. 1986; Sarmaja-Korjonen et al. 2006; Limaye et al. 2007).

Botryococcus:

- Phylum: Chlorophyta, Class: Trebouxiophyceae, Order: Trebouxiales, Family: Botryococcaceae, Genus: *Botryococcus* (**Plate 1.1**).

These densely packed colonial green algae live in surface waters of freshwater and brackish environments and their colonies are common in sediments as old as Ordovician (Martin-Cloasa, 2002) and have proven to be useful paleolimnological indicators (van Geel, 2001; Cook et al. 2011). Their response to the trophic state of water bodies has been noted by researchers such as Guy-Ohlson (1992), Batten & Grenfell (1996), Komarek & Jankovska (2001) and van Geel (2001).

Dinoflagellate Cysts:

- Phylum: Dinoflagellata, Class: Dinophyceae (**Plate 1.1**).

Dinoflagellates are unicellular algae found all over the world in both freshwater and marine environments (Carty, 2003). These organisms are typically motile, having two flagella, one being transverse (along a belt/ cingulum) and the other longitudinal (along a groove/ sulcus) (Fensome et al. 1993). They form resting cysts as part of their lifecycle, which can preserve in sediments (Bravo & Figueroa, 2014). Approximately 20% of thecate or "armoured" dinoflagellate species of the class Dinophyceae Pascher (with cellulose plates lying under the cell membrane) produce fossilizable cysts of dinosporin. The transition to freshwater environments occurred several times during the early Cenozoic in the Order Peridiniales Haeckel, resulting in distinct clades (Luo et al. 2016).

These cysts are useful paleoecological proxies in freshwater ecosystems (e.g., for eutrophication and pH studies) (Zippi et al. 1990, 1991; McCarthy et al. 2011; McCarthy & Krueger, 2013; Danesh et al. 2013; Drljepan et al. 2014; Krueger & McCarthy, 2016). Their association with mesotrophic to eutrophic waters has proven useful in studies with geoarcheological components (e.g., Burden et al. 1986; McCarthy & Krueger, 2013; Krueger & McCarthy 2016; Volik et al. 2016).

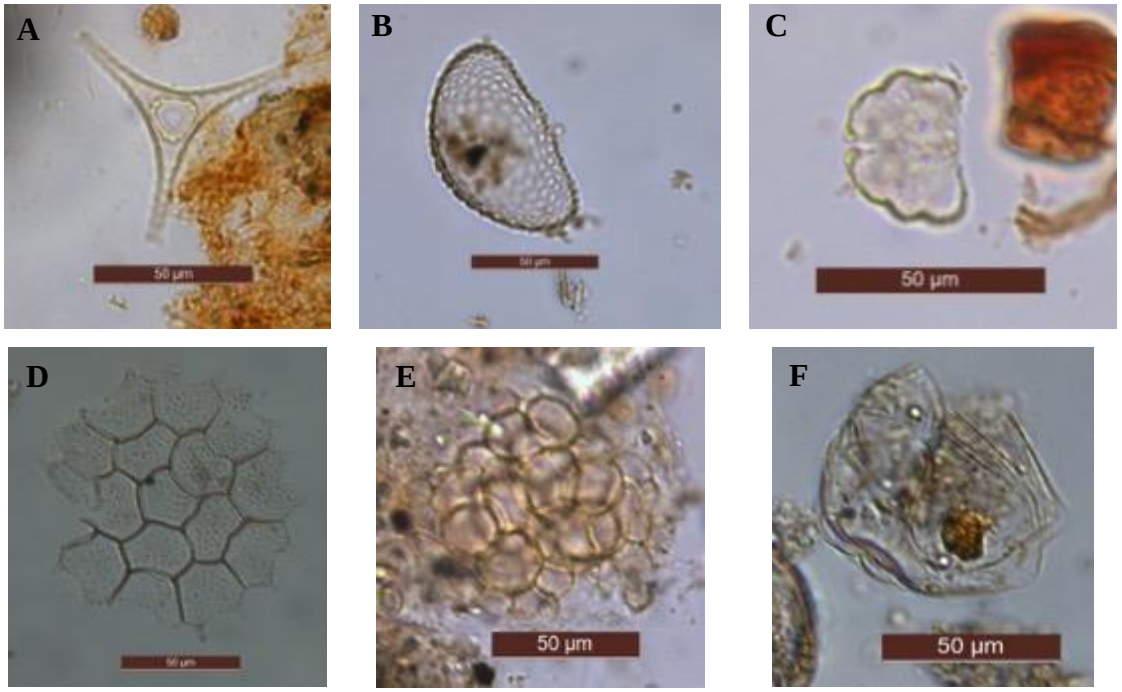

Plate 1.1: Representative algal palynomorphs from Lake Simcoe sediments – desmid half-cells (A. *Staurastrum*, B. *Cosmarium*, C. *Euastrum*); *Pediastrum* coenobia (D); *Botryococcus* colony (E); dinoflagellate cyst (F). Photographs were taken using a Leica MC 120 HD digital imaging camera. Scale bars = 50 µm.

1.3.2 Consumers: Protozoans and Invertebrate Animals

Tintinnid Ciliate:

- Kingdom: Chromista, Phylum: Ciliophora, Class: Spirotrichea, Order: Tintinnida, (**Plate 1.2**).

Ciliates are planktonic protozoans that feed primarily on algae and bacteria using tiny cilia to propel themselves through the water column and to gather food. Most ciliates have little fossilization potential, but the defining characteristic of tintinnid ciliates is a vase-shaped organic-walled lorica. The earliest well-accepted fossil tintinnids (with agglutinated organic-walled loricae) are known from sediments of Jurassic age (Dunthorn et al. 2015). Extant tintinnid ciliates are cosmopolitan in distribution and known from marine, brackish and freshwater environments, but only about ten species inhabit freshwater environments (Tappan, 1993).

The agglutinated loricae of freshwater tintinnids can be mistaken for thecamoebians/ testate amoebae due to their 'vase-like' morphology (Beyens & Meisterfeld, 2001). The

abundance of lorica or outer covering of one such species (*Codonella cratera*) in lacustrine sediments has been associated with eutrophication, increases in heavy metals, increased human population and industry (Barbieri & Orlandi, 1989; Kling, 2005; Danesh et al. 2013).

Rotifers:

- Kingdom: Animalia, Phylum: Rotifera (**Plate 1.2**).

Rotifers are microscopic invertebrate animals found in a wide variety of aquatic (primarily freshwater) environments, who feed on single-celled algae and bacteria using cilia that surround mouths and a pharynx that forms a characteristic masticatory apparatus called the mastax (Segers, 2008). In addition to lorica, the eggs and drought-resistant cysts of rotifers are occasionally reported in studies of NPP from wetland and lacustrine settings (Warner & Chengalath, 1988; van Geel, 2001; Swadling et al. 2001; Turton & McAndrews, 2006). They are particularly diverse and abundant in oligotrophic to mesotrophic, soft and slightly acidic water, although the abundance of some species of *Keratella* were considered a good indicator of eutrophication in Crawford Lake, Ontario (Turton & McAndrews, 2006). The earliest fossil rotifers have been reported from Dominican amber of Eocene age (Waggoner & Poinar, 1993).

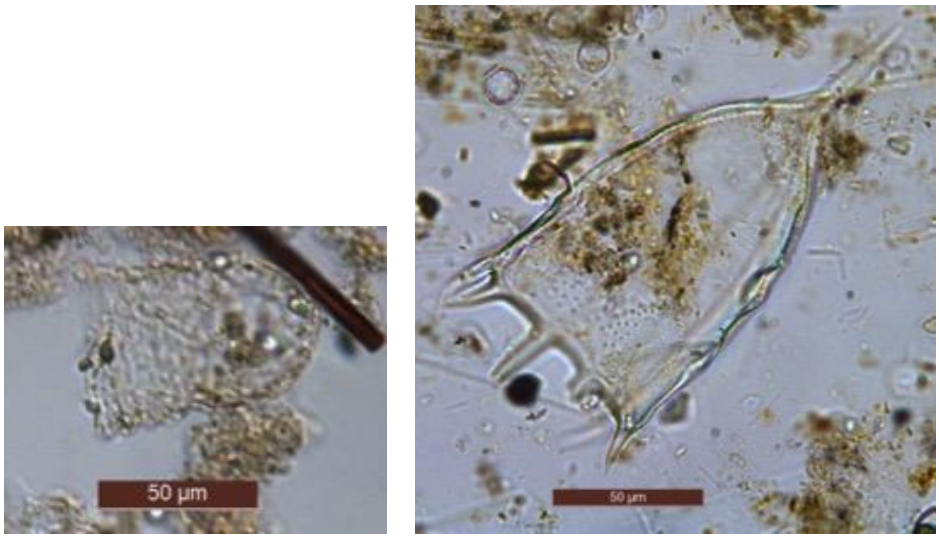

Plate 1.2: Lorica of a tintinnid ciliate *(Codonella cratera)* in a palynological preparation of modern sediments from Lake George, NY (left) and a rotifer in a palynological preparation of modern sediments from Crawford Lake ON (right – photo courtesy of Andrea Krueger). Photographs were taken using a Leica MC 120 HD digital imaging camera. Scale bars = 50 µm.

Chironomids:

- Kingdom: Animalia, Phylum: Arthropoda, Class: Insecta, Order: Diptera, Family: Chironomidae.

Chironomid remains are frequently seen in palynological preparations, but the head capsules of these midge larvae are usually picked out of a known volume of sediment for analysis (Wang et al. 2008). They can be used as a proxy for temperature/ climate reconstruction (e.g., Heiri et al. 2003), hypolimnetic anoxia (e.g., Little et al. 2000) and water quality (e.g., Rodé, 2009).

1.4 Mineralised Microfossils

There are a number of mineralised microfossil groups that are commonly employed in paleolimnological studies, two of which (testate amoebae and diatoms) are described below. Processing techniques for these microfossils depend on composition.

Testate Amoebae:

- Kingdom: Protista, Phylum: Sarcodaria, Class: Lobosa, Order: Thecolobosa, Superfamily: Arcellinida (**Plate 1.3**).

Testate amoebae (i.e., thecamoebians, testate rhizopods or arcellaceans) are unicellular organisms found in freshwater and brackish environments (Roe et al. 2010) who form agglutinated organic-walled tests that can preserve in sediments (Scott et al. 2001). They are primarily benthic protozoans that feed on bacteria (family Centropyxidae, Jung, 1942) or algae (family Difflugiidae, Wallich, 1864) (McCarthy et al. 2015), although one taxon, *Cucurbitella tricuspis* (Stein) attaches to the green alga *Spirogyra* that floats in the water column and thus leads a quasi-planktonic existence (Medioli et al. 1987). Their organic linings are commonly seen in palynological preparations (Payne et al. 2012), but Danesh et al. (2013) found poor agreement between what is found in palynological preparations and traditional sieved samples. These microfossils are often abundant, even if sample sizes are small, and they are good indicators of environmental change (Reinhardt et al. 2005). They have been used to detect changes associated with eutrophication, land

clearance/ deforestation, forest fires, water temperature, pH changes, metals and organic pollutant contamination (Patterson et al. 2002; Roe et al. 2010; Patterson et al. 2012).

Diatoms:

- Kingdom: Chromista, Phylum: Bacillariophyta, Class: Bacillariophyceae (**Figure 1.3**).

Diatoms are unicellular algae with siliceous cell walls that are known to be present in freshwater systems as of the Eocene. In the late nineteenth/ early twentieth centuries diatoms were being used in climate change and pollution studies (e.g., Kolkwitz & Marsson, 1908; Round et al. 1990; Smol & Stoermer, 2010). Today diatoms are used in many studies to assess surface water acidification, eutrophication and climate change (Battarbee et al. 2001).

In Southern Ontario, Reavie & Smol (2001) created a 64-lake calibration data set for diatom/lake chemistry, which has been used for transfer functions (e.g., Ekdahl et al. 2004, 2007). Diatom analysis by Hawryshyn (2010) from the main basin of Lake Simcoe highlights a potential problem, where low abundances (possibly due to dilution) prevent study prior to the mid-nineteenth century. Ekdahl et al. (2004) show an increase in planktonic diatom abundance and decrease in benthic diatom abundance, responding to the input of nutrients due to increased siltation from land clearing, in two periods in Crawford Lake, Ontario (Iroquoian and Euro-Canadian).

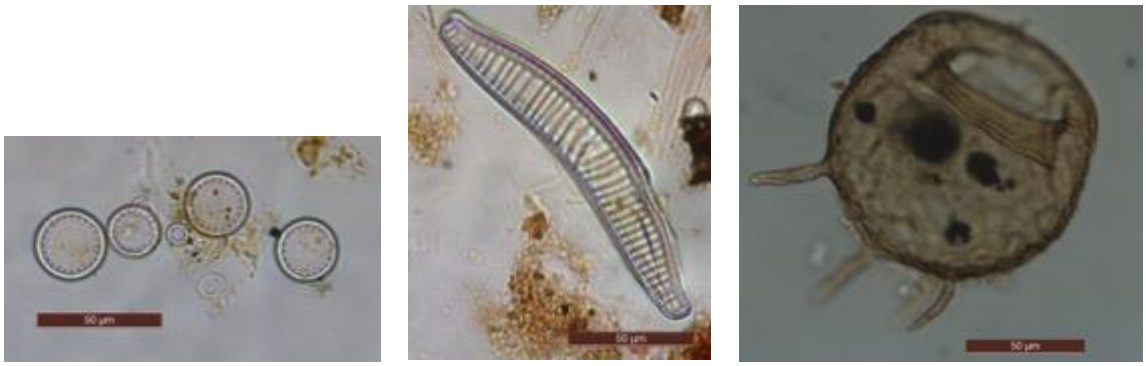

Plate 1.3: Mineralized microfossils – centric diatom (left); pennate diatom (middle); centropyxid thecamoebian/ testate amoeba (right) in modern sediments from Lake Simcoe. Photographs were taken using a Leica MC 120 HD digital imaging camera. Scale bars = 50 µm.

1.5 Microfossils & Archaeology

The use of microfossils in archaeology is relatively new. It was only in the 1930s, and before the advent of radiocarbon dating, that archaeologists began using fossil pollen as a dating tool. To do this, pollen assemblages analyzed at archaeological sites were compared to well-understood assemblages from nearby lakes and bogs (Bryant & Holloway, 1996). Iversen (1941) promoted the utility of microfossils in archaeology, building on the pioneering work of von Post et al. (1925), showing the migration of agricultural practices to northern Europe, as well as the species cultivated. The application of palynological analysis to archaeology was delayed in North America where more palynologists were focused on glacial history (Bryant & Holloway, 1996).

1.5.1 Native American Settlement in Ontario

Sonnenburg et al. (2011, 2012, 2013) conducted studies at Rice Lake where pollen and testate amoebae (i.e., thecamoebians) were employed, revealing environments exploited for resources by Paleo-Indian peoples and later Archaic peoples. The presence of a previously unknown wetland area was revealed by testate amoeba analysis, which corresponded to the discovery of microdebitage, indicating resource exploitation 10,500 calibrated years before present (cal. BP). Microdebitage are microscopic stone flakes from tool production (Sonnenburg et al. 2011). The study of Sonnenburg et al. (2013) is the first where testate amoebae have been used to reconstruct submerged archaeological landscapes and for the identification of potential areas of archaeological interest in North America. In addition, they discuss the usefulness of testate amoebae in identifying water-level and trophic status fluctuations which discerned the Early Holocene low stand (where pollen response was more subtle) and small differences between lake basins.

Palynological analysis (e.g., AP, NAP, dinoflagellate cysts and *Pediastrum* coenobia) of sediment cores from Second Lake and Lake Gignac in Awenda Provincial Park revealed two forest clearing and farming events, with an intermediary forest recovery (Burden et al. 1986). The first event was attributed to the Wendat/ Huron people, between the mid-fifteenth and mid-seventeenth centuries (discussed further in **Chapter 4**). The second was attributed to early European settlement in the 1800s. Both events resulted in increased NAP abundance (new growth in cleared areas) followed by forest succession in

abandoned fields and a similar algal palynomorph response to nutrient loading (as discussed in **Section 1.3** and shown in **Figure 1.2**). Aside from the rare presence of the cultivar pollen *Zea* (corn), there is little indication of Wendat impact in the pollen record, as discussed in **Section 1.3**, but increases in *Pediastrum* and cysts attributed to *Peridinium willei* at the expense of cysts of *Peridinium wisconsinense* record cultural eutrophication associated with both human impact zones (both Wendat and Euro-Canadian). A similar algal response to Wendat and Euro-Canadian settlement was noted across Severn Sound in a core from Honey Harbour where there was no increase in NAP associated with Native impact (McCarthy et al. 2011).

Many researchers have studied sediments from the varved meromictic Crawford Lake (Ekdahl et al. 2004, 2007; Turton & McAndrews, 2006; McAndrews & Turton, 2010; McCarthy & Krueger, 2013; Krueger & McCarthy, 2016). Microfossil analyses (e.g., pollen, NPP, diatoms, rotifers and dinoflagellate cysts) identified an Iroquoian signature which included the presence of cultivar pollen, peaks in dinoflagellate cyst abundance, abrupt changes to the diatom and rotifer communities with no recovery to pre-disturbance state and increased rotifer abundance (**Figures 1.3-1.5**). Finlayson (2004) noted that the pollen analysis of this lake (e.g., Boyko, 1973; Byrne & McAndrews, 1975) contributed to revisions of the Ontario Iroquoian chronology.

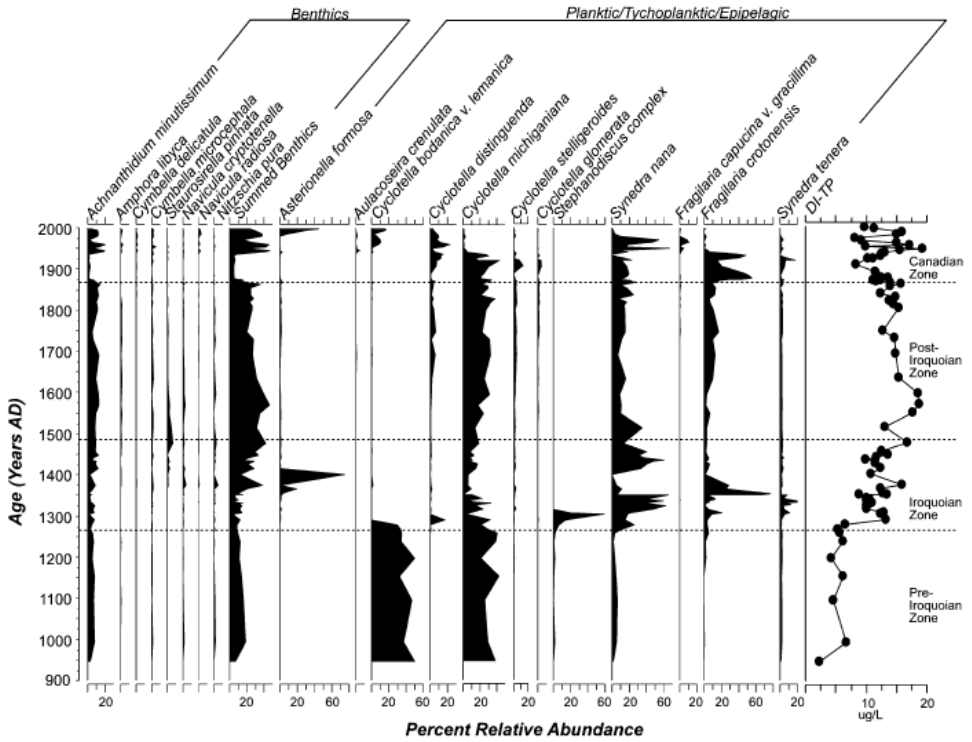

Figure 1.3: Diatom assemblages from Crawford Lake (Ekdahl et al. 2007). The abundance of planktonic taxa increases in the Iroquoian zone, as does total phosphorus (diatom inferred total phosphorus – DI-TP) and the assemblage does not recover (to a pre-disturbance state) in the post-Iroquoian period. The increase in planktonic organisms, caused by increases nutrient loading, is detrimental to benthics as it lowers dissolved oxygen concentrations and reduces light penetration. Radiocarbon dating from core CL1-F01indicated that the base of the Canadian zone is between 1840 – 1860, as opposed to the latter half of the nineteenth century as detailed above (Ekdahl et al. 2004; Geological Society of America, n.d.).

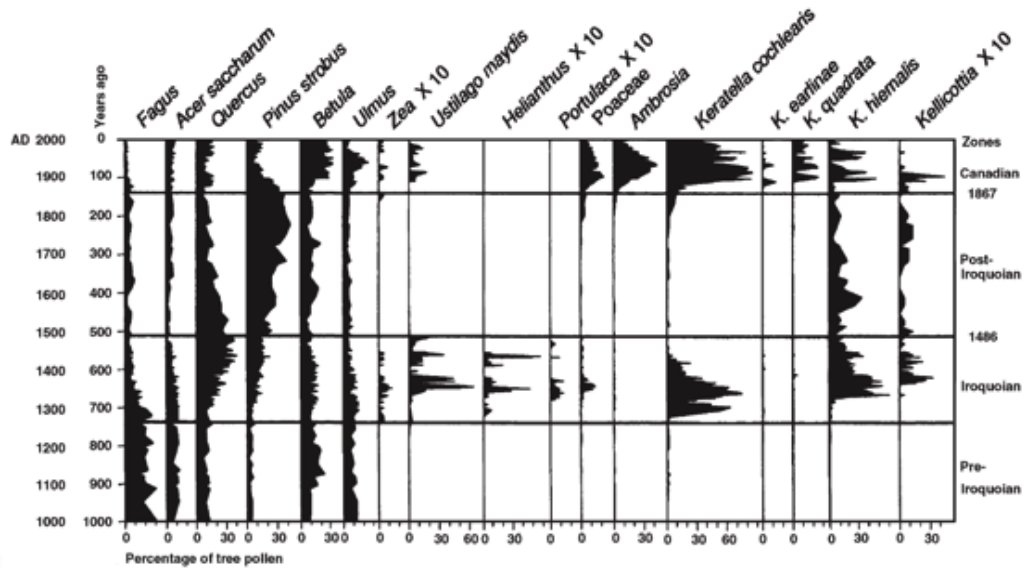

Figure 1.4: Pollen and NPP assemblages from Crawford Lake (Turton & McAndrews, 2006). Cultivars/ fungal cultivar indicators, such as *Helianthus* (sunflower), *Zea* (corn pollen) and *Ustilago maydis* (corn smut), appear in the Iroquoian zone. *Zea* and *Ustilago maydis* also appear in the Canadian zone. Rotifer lorica abundance increases in the Iroquoian zone and the assemblage does not recover (to a pre-disturbance state) in the post-Iroquois period. The base of the Canadian zone is shown to occur in the latter half of the

nineteenth century (i.e., 1867, year of Canadian Confederation), however radiocarbon ages from core CL1-F01 (from five pine needles and twigs between 25.65 to 26.83 cm) are more consistent with an ages 1840 - 1860 (Ekdahl et al. 2004; Geological Society of America, n.d.).

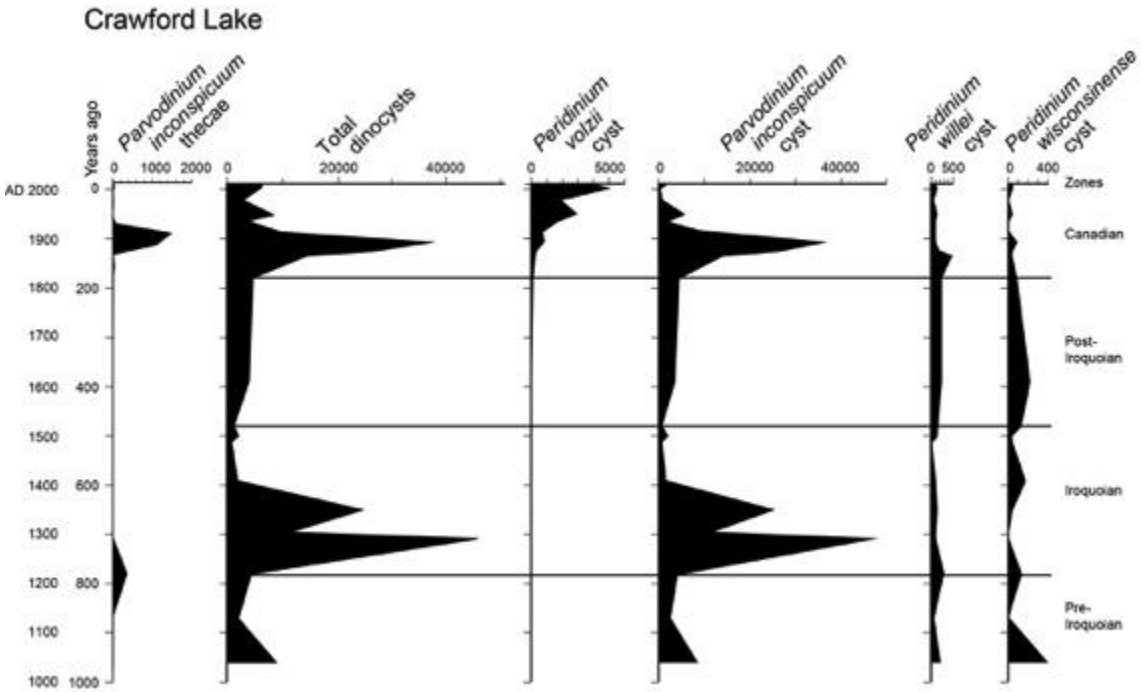

Figure 1.5: Dinosporin cysts and rarely fossilized cellulosic thecae of dinoflagellates (shown as absolute abundances per ml sediment measured by liquid displacement) in varved sediments from Crawford Lake (Krueger & McCarthy, 2016). Peak dinocyst abundances near the base of the Iroquoian zone suggest that the peak impact on the lake ecosystem was shortly after the village was settled and peak impact in the Euro-Canadian phase coincides with operation of the lumber mill in the late nineteenth century.

Since Iversen demonstrated the movement of agricultural practices into Northern Europe (Bryant & Holloway, 1996), many researchers have used pollen to assess agriculture, which can provide insights to diet based on cultivars. For example, in sediments collected from Crawford Lake, Ontario, an abundance of corn and sunflower pollen was identified from time periods coinciding with Iroquoian occupation of the area (McAndrews et al. 1971). The 'Three Sisters' (corn, beans, and squash) are a well-known dietary staple for many Native American tribes. The discovery of cultivar pollen in Crawford Lake sediments led to the discovery of a nearby village (Byrne & McAndrews 1975). Between 1973 to 1987 excavations at the site uncovered 11 longhouses and many artifacts. Three of the longhouses (and other features) have been reconstructed on the site, which now serves as an educational attraction (Conservation Halton, 2016).

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Chapter 2: The Effect of Acetolysis on Desmids

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2.1 Introduction

Although the term 'palynomorph' is often considered to be synonymous with pollen (and embryophyte spores), many non-pollen palynomorphs (NPP) are also found in palynological preparations. Because they contain representatives from all kingdoms of life, NPP are useful proxies of terrigenous and aquatic environments, past and present, with most NPP groups being useful in paleolimnological studies (van Geel, 2001).

The acetolysis technique, introduced by Erdtman in 1934, is an oxidizing method common in palynological preparation and it is particularly useful for pollen analysis as it clears 'unwanted' organic matter from slides (Bennett & Willis, 2001). While the usefulness of the technique to pollen analysts is evident, several researchers have detailed concerns over its use in certain circumstances. Reid (1977) and Marret (1993) observed the selective destruction of dinoflagellate cysts belonging to the families Polykrikaceae and Protoperidiniaceae (Mertens et al. 2009), while Marret (1993), Mudie & McCarthy (2006) and Mudie et al. (2010) noted a negative impact on thin-walled microfossils. Even with regard to pollen analysis, several concerns have been noted. For example, Havinga (1964, 1967) demonstrated the differences in preservation potential among common anemophilous plants, while Hesse & Waha (1989) noted the destruction of non-sporopollenin pollen components (e.g., cellulose). As these concerns are with regard to established paleoproxies that are of increasing interest to researchers, further investigation into the effects of acetolysis is warranted.

Desmids (**Plate 2.1**) are conjugate microscopic green algae (Division Charophyta, Class Zygnemophyceae, Order Desmidiales) that are common in freshwater environments, with a general preference towards oligotrophic-mesotrophic waters that have low conductivity. These organisms have varied ecology, with most species being benthic, though planktonic species exist, including most species from the genus *Staurastrum* Meyen ex Ralfs (1848). Other common desmid genera include *Cosmarium* Corda ex Ralfs (1848) found in oligotrophic to eutrophic settings and *Euastrum* Ehrenberg ex Ralfs (1848) found primarily in oligotrophic settings (Graham & Wilcox, 2000; Gerrath, 2003). Desmids are commonly used as water quality indicators in modern lakes by limnologists and phycologists. For example, Gerrath (2003) notes that some *Staurastrum spp.* are good indicators of nutrient loading and Ngearnpat & Peerapornpisal (2007) describe several species that may be used as water quality indicators in a 12-site study from Thailand. Additionally, their remains in lakebed sediment from a reclamation pond in Fort McMurray, Alberta showed a strong positive response to nutrient loading between 1992 and 1996, allowing recommendations to be made to oil sands producers (Garner, 2015; McCarthy et al. 2015).

Charophytes are common in the fossil record as of the Neogene (23-2.6 million years ago) and may be present as far back as the Devonian (419.2-358.9 million years ago) (Krutzsch & Pacltova, 1990; Head, 1992; Worobiec, 2014). Desmids half-cells, as well as other freshwater NPP, have been used to trace fluvial transport to near shore marine environments (Hill et al. 1985; Matthiessen et al. 2000; Mudie et al. 2010; Mudie et al. 2011). Half-cells of desmids, particularly those belonging to the genera *Cosmarium*, *Euastrum* and *Staurastrum*, were common in palynological preparations from Lake Simcoe (Danesh et al. 2013; Volik, 2014), Sluice Pond (Garner, 2015; Krueger et al. 2015) and Crawford Lake (McCarthy et al. 2013), where they proved to be useful paleolimnological proxies in conjunction with other NPP, particularly of anthropogenic impact. Volik (2014) found that desmids, along with other NPP in a long piston core from the main basin of Lake Simcoe (site LS07 PC5; **Figure 2.1**), were sensitive to climatic and hydrological changes through the Holocene. None of these samples were acetolysed, which may explain their abundance and diversity in these palynological

studies – particularly in Crawford Lake, where several previous palynological studies that used acetolysis in their sample preparations did not mention desmid occurrences (Ekdahl et al. 2004, 2007; Turton & McAndrews, 2006; McAndrews & Turton, 2010).

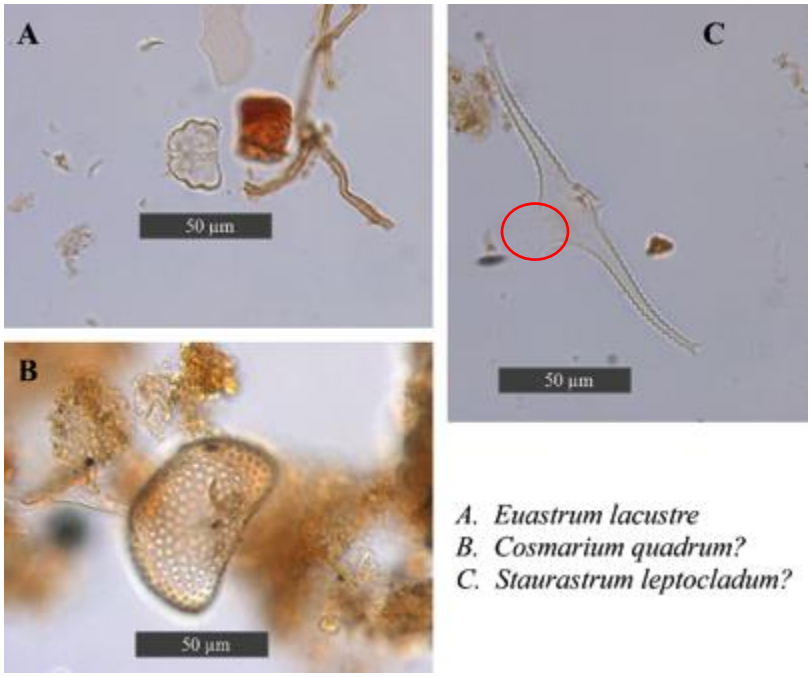

Plate 2.1: Common desmids found in acetolysed preparations from Lake Simcoe: A. The genus *Euastrum*, with half-cells that have many indentations; B. *Cosmarium*, with semicircular half-cells (semicells) lacking indentation and ornamentation, was the most common after acetolysis, probably due to its robust morphology; and C. *Staurastrum*, which are primarily planktonic varying in shape and have ornamentation and processes tipped with spines (two or more processes per half-cell; note that one end of this specimen is broken (red circle), probably as a result of acetolysis.

This study assesses the impact of acetolysis on desmids using samples from core SB-1 collected from Smith's Bay in Lake Simcoe (Volik, 2014). Samples were initially processed and analyzed without oxidizing techniques. Up-core changes in desmid concentrations and species assemblages are compared with other, better understood microfossil proxies of water quality. Acetolysis was subsequently applied on the same sample residues and the samples were reanalyzed. Sparse desmid assemblages in these slides could not be interpreted paleoecologically.

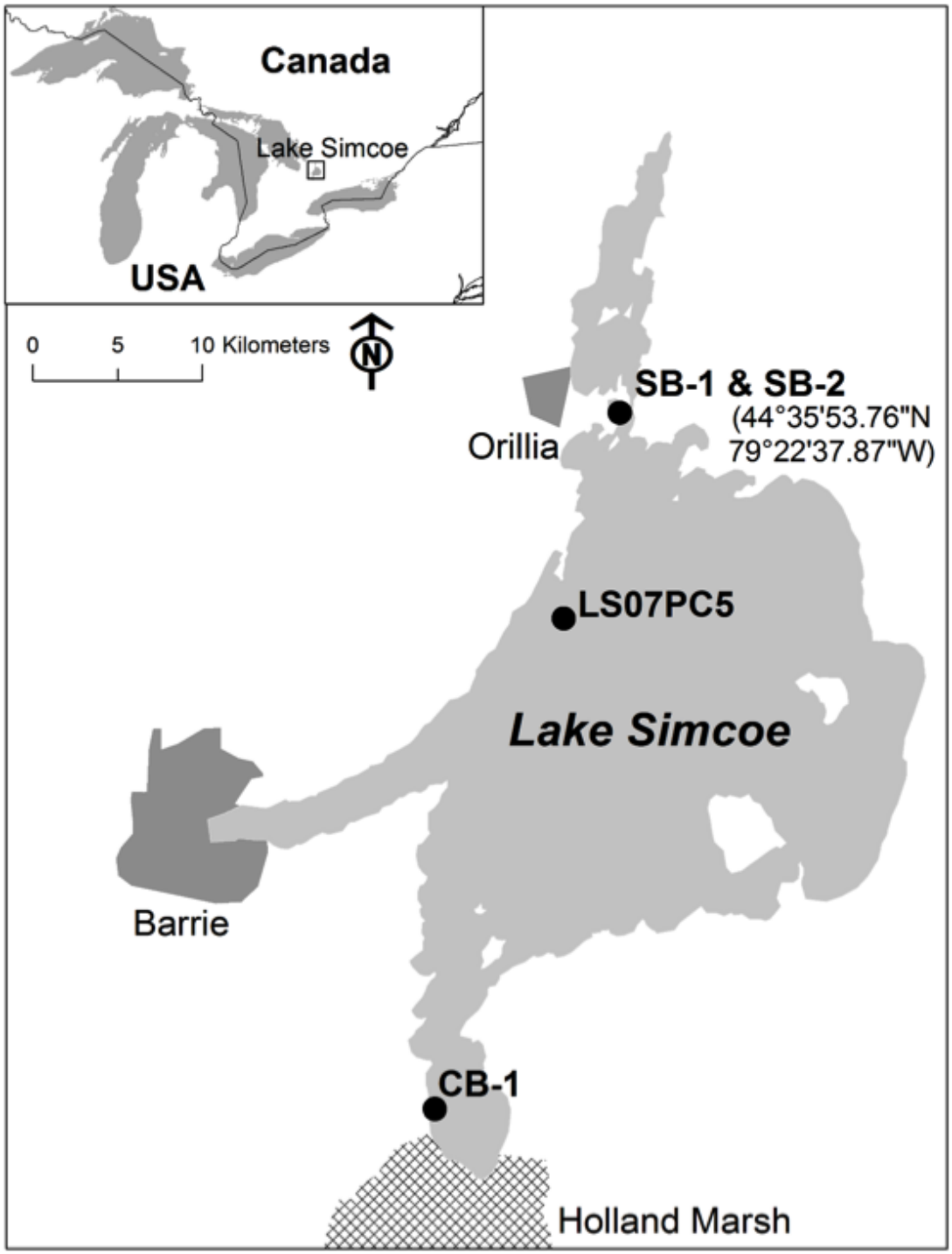

Figure 2.1: Lake Simcoe is the largest lake in Ontario other than the Laurentian Great Lakes, and it is part of the Lake Huron/ Georgian Bay watershed. Desmids in core CB-1 from Cook's Bay were shown to respond to draining of the Holland Marsh in the early twentieth century, and to the post-WWII population boom in the drainage basin (Danesh et al. 2013). Finally, a long-post-glacial record from core LS07 PC5 illustrated their response to changing climate and hydrology throughout the Holocene (Volik, 2014). See detailed bathymetry and entire watershed in **Appendix C**.

2.2 Methods

An 80-cm-long sediment core (SB-1) was collected from Smith's Bay at a water depth of 2.15 m using a Rowley Dahl sampler (Volik, 2014). Smith's Bay is in the northernmost part of Lake Simcoe, near the outlet to the Severn River that flows into Georgian Bay/Lake Huron via Lake Couchiching (**Figure 2.1**). Lake Simcoe is the largest lake in Ontario other than the Laurentian Great Lakes. It is part of the Lake Huron/ Georgian Bay watershed and has a residence time of approximately 11 years (Danesh et al. 2013). Humans have been settling within these watersheds since before recorded history. For example, the Wendat (commonly referred to as the Huron) farmed the area between ca. 1450 and 1650 CE (McCarthy et al. 2011).

2.2.1 Palynological Processing

Subsamples of 5 mL (measured using liquid displacement) from core SB-1 were collected every 5 cm down-core for palynological analysis at Brock University, using techniques slightly modified from Faegri & Iversen (1975). Clayey sediments were disaggregated using 0.02% sodium hexametaphosphate (commonly called Calgon^{TM}, although modern Calgon is phosphate free) and a tablet containing 10,850 (±200) *Lycopodium clavatum* spores was added to quantify palynomorph concentrations following Stockmarr (1971). Carbonates were dissolved using 10% hydrochloric acid (HCl) in a warm water bath for 30 minutes, and silicates were subsequently dissolved using 48% hydrofluoric acid (HF) in a warm water bath for 30 minutes. Samples were centrifuged and decanted after each step, residues were sieved using a Nitex© mesh with 10-mm openings and slides were mounted using glycerine jelly (Volik, 2014).

Samples were analyzed using a Leica DMLB light microscope at 400x magnification (Volik, 2014). NPP were identified using a variety of sources, including Beyens & Meisterfeld (2001), Komarek & Jankovska (2001), John et al. (2002), Wehr & Sheath (2003) and Coesel & Meesters (2007). The same sample residues were acetolysed using methods as described by the University of Ottawa Laboratory for Paleoclimatology and Climatology (LPC) protocol (Gajewski, 2009). Water was removed from residues using glacial acetic acid and a 9:1 acetic anhydride/sulfuric acid solution was added, and test tubes were placed in a warm water bath for 4 minutes. Samples were rinsed with glacial

acetic acid and then distilled water. Samples were centrifuged and decanted after each step, and slides were mounted using glycerine jelly. Analysis of acetolysed samples was completed using a Leitz light microscope at 400x magnification, with photographs collected using a Leica MC 120 HD camera. Desmid identifications follow Volik (2014) and references therein.

2.2.2 Loss-on-Ignition (LOI) and Geochemical Analysis

In 2014, a replicate 91-cm sediment core (SB-2) was collected from Smith's Bay and analysed for LOI at Brock University and for chemical analysis of nitrite (NO^2), nitrate (NO^3), total phosphorus (TP) and heavy metals, completed by a Canadian Association for Laboratory Accreditation (CALA)-certified laboratory. Methodology for LOI analysis followed Dean (1974). Subsamples were collected at 10-cm intervals, weighed and placed into an oven to dry (24 hours at 105°C). Once dry, these subsamples were reweighed and placed in a muffle furnace set to 550°C for at least 1 hour to burn off organic matter. The samples were then reweighed and returned to the muffle furnace at 950°C (for at least an hour) to remove carbonates. Finally, the samples were weighed once more and, following Heiri et al. (2001), the actual carbonate fraction was determined.

2.3 Results

Samples from core SB-1 that had not been acetolysed contained relatively high concentrations (up to 111,000 half-cells/ mL) of several species of the desmid genera, primarily *Cosmarium*, *Euastrum* and *Staurastrum*, except for two intervals. *Cosmarium pseudopyramidatum/ C. pyramidatum* dominate the assemblage below 35 cm, except in samples from 55 and 60 cm where *C. protractum* and *C. punticulatum/ C. granatum* co-dominate with *C. pseudopyramidatum/ C. pyramidatum*. *C. franzstonii* and *Euastrum lacustre/ E. luetkemuelleri* do not persist through the lower sparse zone. Sediments in the upper 15 cm contain relatively high concentrations of *C. protractum* and *C. punticulatum/ C. granatum* in an assemblage rich in *C. botrytis, C. depressum, C. protractum, Staurastrum planctonicum/ S. pingue* and *S. chaetoceras*. A transitional assemblage is characterised by common *C. variolatum/ C. subcucumis/ S. subcrenatum*, and *E. bidentatum/ E. denticulatum* together with *C. fornulosum/ C. reniforme* and several other

species of *Cosmarium* characterize another sparse interval from 30-15 cm. The base of this interval is marked by *S. siebaldi* and *S. puncticulatum*, and neither *C. pseudopyramidatum/ C. pyramidatum* nor *C. variolatum/ C. subcucmis/ C. subcrenatum* is found above this upper sparse zone (**Figure 2.2**).

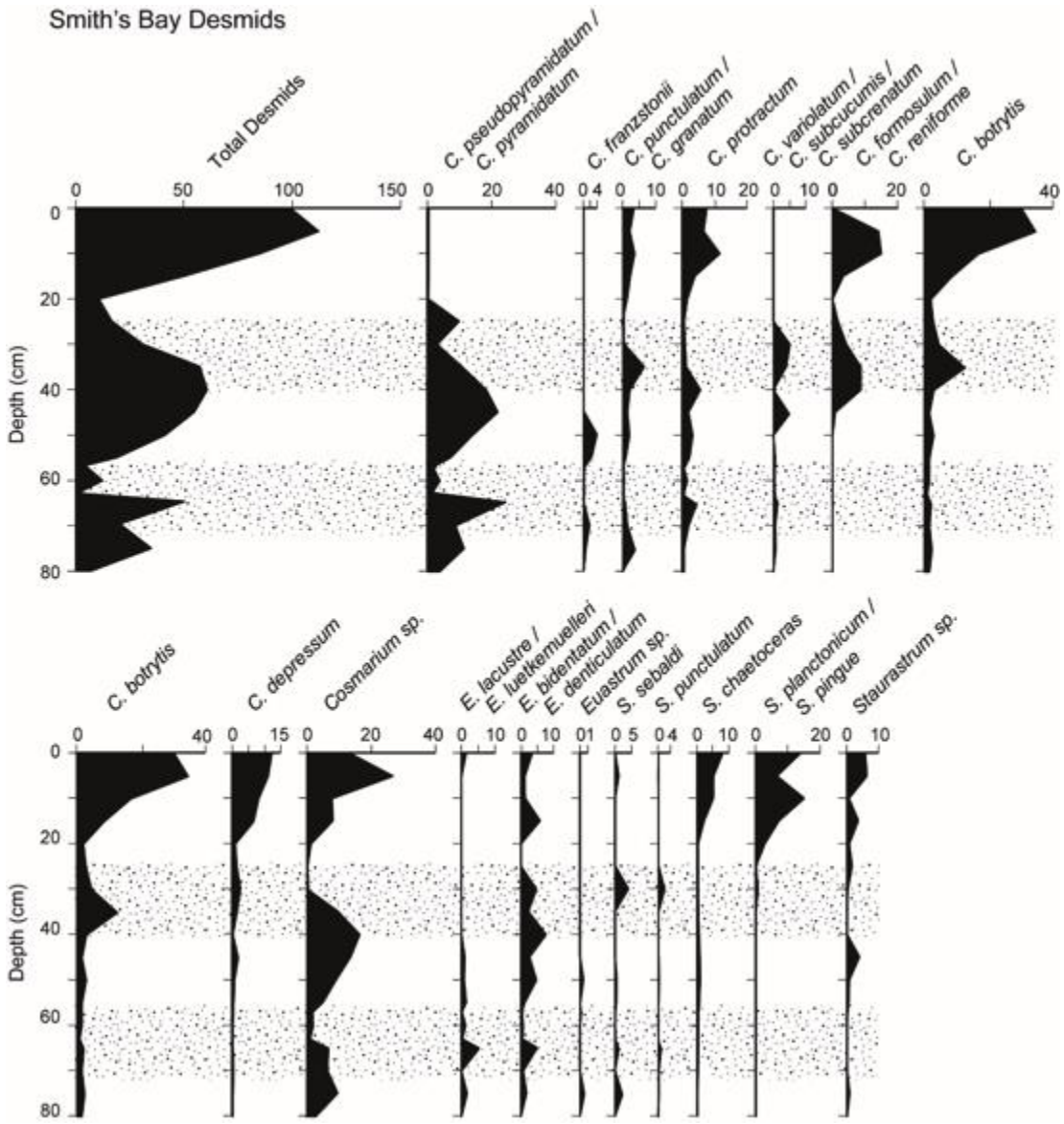

Figure 2.2: Unacetolysed palynological preparations from core SB-1 (Volik, 2014) contain a diverse desmid flora, illustrated as absolute abundances of half-cells (x1000/mL). Abundant *Cosmarium pyramidatum/ C. pseudopyramidatum* and various *Euastrum spp*. record oligotrophic-mesotrophic conditions below 35 cm in the core, except in the samples from 50 and 60 cm. Abundant *C. botrytis* and *C. protractum* together with *Staurastrum chaetoceras* and S. *pingue/ planctonicum spp*. in the upper 15 cm of the core record eutrophic conditions.

LOI and geochemical analysis of the SB-2 core (**Figure 2.3**) show highly calcareous sediments (marls) with nutrient and heavy metal peaks at two intervals: (i) at 60 cm, nitrite, nitrate, chromium, copper and zinc levels increase; and (ii) nitrite, nitrate, zinc and lead levels above the *Ambrosia* rise (ragweed rise), with TP increasing slightly at the top of the core.

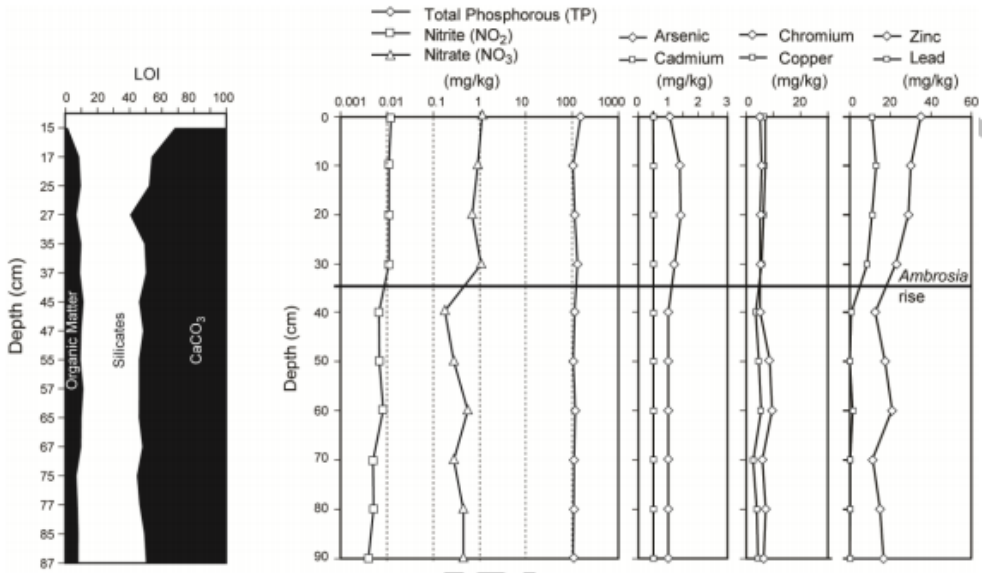

Figure 2.3: Loss-on-ignition (LOI) and geochemical results from SB-2 show that the core is primarily calcareous, with little organic variations. Increases in silicates in the upper 30 cm, reflect siltation from regional development (see **Chapter 3**, increases in planktonic desmid taxa). At the 60 cm interval and above the ragweed rise, increases in nutrients and heavy metals concentrations are attributed to increased siltation. LOI was not completed for the top of the core due to core extrusion techniques where the upper 15 cm were loose and sediment was used up on other analytical testing.

Analysis of the desmid assemblage pre- and post-acetolysis reveals a decrease in abundance (mean = 87%), with three small spikes, and skewing of the up-core trend, in post-acetolysis sample residues (**Figure 2.4**). *Cosmarium* made up 73% of the 'surviving' assemblage, in which *C. depressum, C. pseudopyramidatum/ C. pyramidatum* and *C. formosulum/ C. reniforme* were identified most frequently. Sixteen percent of the assemblage was *Staurastrum*, most of which were planktonic species; however, the benthic species *S. punctulatum* was also observed. The remaining 11% of the assemblage was *Euastrum*, with *E. bidentatum/ E. denticulatum* and *E. lacustre/ E. luetkemuelleri* among the species observed.

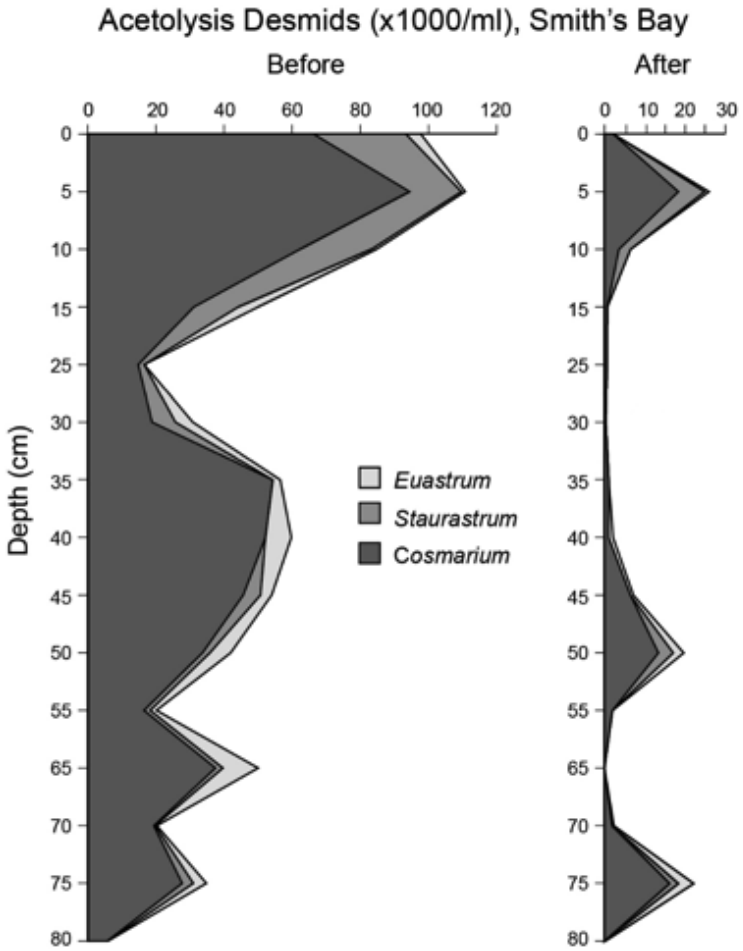

Figure 2.4: A comparison of pre- and post- acetolysis residues from the SB-1 core reveals significantly reduced abundance of desmids (x11000 half-cells/ mL). In post-acetolysis residues, there are three spikes in desmid abundance, attributed to either a methodological variation or the presence of gastropods and organic debris that exhausted the acetolysis solution. The abundance post-acetolysis does not reflect original abundance, and the assemblages are skewed towards half-cells of *Cosmarium spp*.

2.4 Discussion

An abundant and diverse desmid flora was found in samples from core SB-1 that had not been acetolysed, and assemblage changes observed up-core can be related to various phases of anthropogenic impact (**Figures 2.2** & **2.5**). The appearance of common *Staurastrum spp.* in the upper 35 cm of the core coincides with an increase in nutrients (TP, NO^2 & NO^3) and the heavy metals lead and zinc associated with increased siltation (**Figures 2.2** & **2.3**). This is consistent with the dominantly eutrophic and planktonic ecology of this desmid genus, and the abundance of *Ambrosia* (ragweed pollen) associates this with Euro-Canadian settlement of the region beginning in the mid nineteenth century (Chittenden 1990). An earlier increase in nutrients and the heavy metals chromium, copper and zinc, around 60 cm in the core, is attributed to Wendat

agriculture (**Figure 2.3**) (see **Chapter 4**). According to Heidenreich (1971), the French explorer Samuel de Champlain described the Wendat landscape as 'cleared, with many open fields and meadows'. They farmed the land, growing crops like maize, beans and squash between ca. 1450 and 1650 CE, when they were expelled from the region by the Iroquois (McCarthy et al. 2011). At both the 35-cm and 60-cm intervals, there is a decrease in desmid concentrations, probably due to the effect of siltation on light penetration through the water column (**Figure 2.5**).

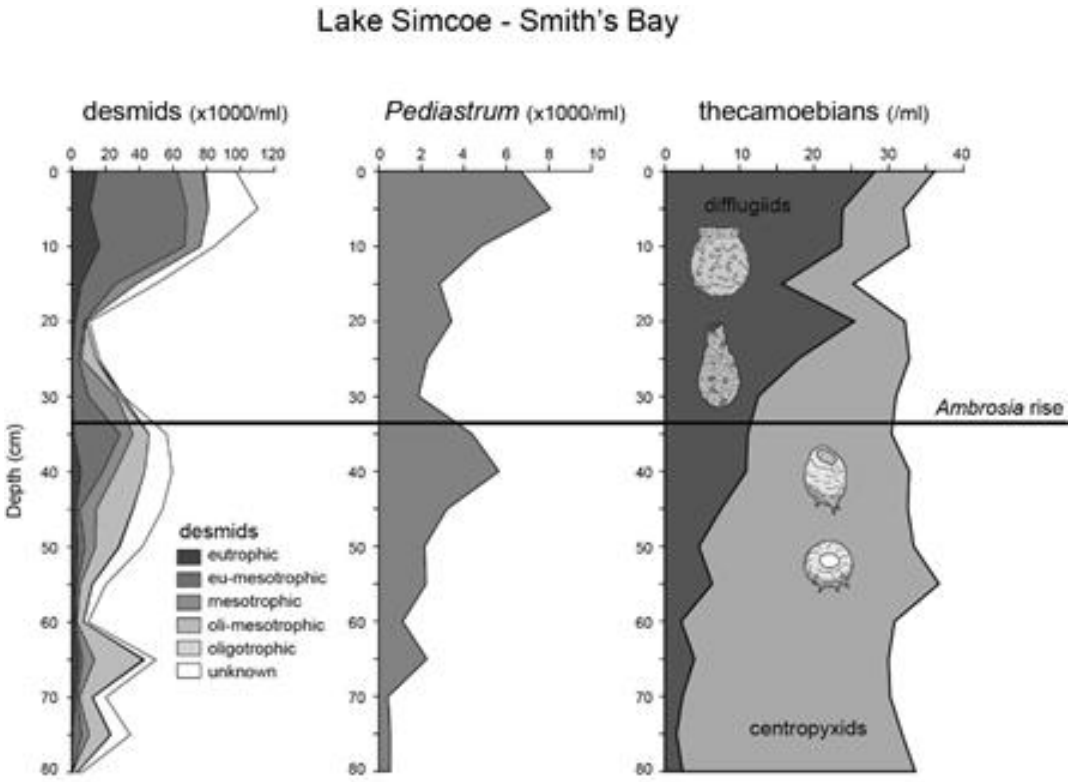

Figure 2.5: Desmid assemblages (x1000 half-cells/ mL) analyzed by Volik (2014) from unacetolysed preparations and grouped by trophic status following Šťastný (2010) show an up-core trend from oligo-mesotrophic varieties to eu-mesotrophic and eutrophic varieties. The decrease in desmid abundance at 65 cm and at the base of the ragweed rise (*Ambrosia*) around 33 cm, also seen in the *Pediastrum* record, is consistent with the attribution to increased siltation. The increase in difflugiid thecamoebians relative to centropyxid taxa records increasing eutrophication up-core, with a slight increase around 55 cm and a larger increase around 20 cm, but the desmids appear to be even more sensitive proxies of water quality. Major changes in all microfossil groups are attributed to anthropogenic impact by the Wendat between ca. AD 1450-1650 and Euro-Canadians since the mid nineteenth century.

The up-core trend in desmid assemblages, organized by trophic status using Šťastný (2010), combined with the *Pediastrum* and thecamoebian (testate amoeba) findings of Volik (2014) show a trend towards a more eutrophic environment in Smith's Bay. The desmid assemblage shifts from oligo-mesotrophic to eu-mesotrophic, as *Pediastrum*

abundance increases and difflugiid thecamoebians become dominant over the centropyxids (**Figure 2.5**). *Pediastrum* species tend to prefer nutrient-rich water (Shubert, 2003), while algivorous difflugiid thecamoebians (McCarthy 1984) dominate eutrophic lakes with high TP (Roe et al. 2010; Patterson et al. 2012).

A significant decrease in desmid abundance is observable when comparing pre- and post-acetolysis results, with the genus *Cosmarium* appearing to be the most likely to survive (it comprised 73% of the post-acetolysis assemblage), possibly due to its robust morphology. Several peaks in desmid abundance can still be discerned in post-acetolysis data, though they are muted (**Figure 2.4**). These peaks may be the result of methodological variance (e.g., minor differences in the duration of exposure or the efficiency of mixing to ensure equal exposure throughout the sample). Although the LOI (**Figure 2.3**) values were relatively low and constant concentrations of organic matter were found through the marly sediments of Smith's Bay, exceptionally high concentrations of gastropods were observed around 5 and 50 cm, and increased plant material was observed at 75 cm, so it is possible that the acetolysis mixture was consumed eliminating this debris, leaving higher quantities of desmids untouched.

While analyzing the desmid assemblage pre- and post-acetolysis, it was noted that higher numbers of some other non-pollen palynomorphs, notably *Pediastrum*, were identified. *Pediastrum* may be easier to observe after 'unwanted' organic material is removed, no longer obscuring these low-relief palynomorphs (**Plate 2.2**). This probably explains the frequent mention of *Pediastrum* in conventional palynological studies (Burden et al. 1986; Pollingher, 1986; Zippi et al. 1990).

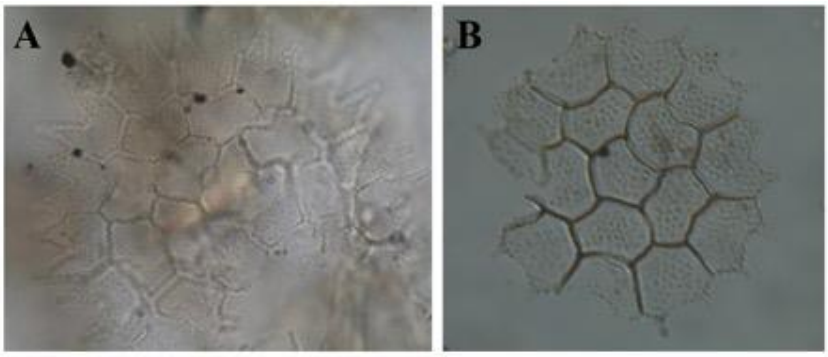

Plate 2.2: *Pediastrum* coenobia can be observed pre- (A) and post-acetolysis (B), although they are much clearer in B compared to A, as the 'clouding' amorphous organic material has been removed (Photo A reproduced with permission from Volik, 2014).

According to Blokker et al. (1998), *Pediastrum boryanum* is composed of highly resistant, non-hydrolysable aliphatic biopolymers, a concept reiterated by van den Hoek et al. (1995), who stated that cell walls of *Pediastrum* are reinforced with a sporopollenin-like material. *Pediastrum* has been observed in statistically significant abundances in samples that have been processed with (e.g., Burden et al. 1986) and without (e.g., Danesh et al. 2013) the use of acetolysis, but further research is recommended to understand how the abundance and diversity of *Pediastrum* assemblages change pre- and post-acetolysis.

2.5 Conclusion

Despite being present in the fossil record back through the Neogene (and, possibly, Devonian) desmids are seldom reported in palynological/ micropaleontological studies. This is almost undoubtedly due to the pervasive practice of acetolysis. Although this oxidizing step is effective in clearing slides of organic debris to make pollen analysis more efficient, it is also destructive to susceptible palynomorphs, and its deleterious effects have been shown for Black Sea surface sediments (Mudie et al. 2011). The use of NPP as paleoproxies is becoming more popular, each one providing a piece to a larger picture. Therefore, the loss of any palynomorph due to acetolysis can result in a preventable loss of knowledge or insight. Analysis of the same sample pre and post-acetolysis revealed a reduction in the abundance of desmid half-cells in slides by 37-100% (mean 87%), skewing the assemblage towards the more robust *Cosmarium spp*. Whereas species assemblages prior to acetolysis record changes in water quality associated with two distinct intervals of human settlement in the Lake Simcoe watershed,

the presence of desmids in the same residues following acetolysis appear to reflect taphonomic rather than ecologic factors (i.e. enhanced preservation due to gastropod or organic debris).

Given the importance and versatility of desmids and other NPP as paleolimnological indicators, the following recommendations are made with regard to acetolysis:

- Omit oxidizing techniques from palynological methodology as pollen and oxidation-resistant NPP can be observed without it; or
- Use a two-pronged approach, where desmids and other NPP are analyzed prior to acetolysis, followed by acetolysing the same residues and analyzing pollen (possibly acetolysis-resistant NPP like *Pediastrum*), thus benefiting from the technique.

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Chapter 3: Non-Pollen Palynomorph Evidence of Human Impact on Lake Simcoe: Applications for Water Resource Management

3.1 Introduction

Non-pollen palynomorphs (NPP) are the acid-resistant remains of organisms, with representatives from all kingdoms of life. Their diverse life habits and varied environmental preferences make them excellent proxies of past environmental conditions and human impact (van Geel, 2001; Haas, 2010). The remains of protozoans (e.g., testate amoebae and tintinnid ciliates) and microscopic animals (e.g., chironomids) represent consumers in the same slides containing algal palynomorphs (primary producers), providing insights into the entire lake ecosystem. Fungal spores and hyphae and plant stomata augment the pollen record, allowing upland conditions (notably forest fires and land-clearing for agriculture and urbanization) to be reconstructed.

Several studies have demonstrated the potential of algal palynomorphs for reconstructing the depth, salinity, temperature, pH, and nutrient status variables of aquatic paleoenvironments (e.g., Jankovska & Komarek, 2000; van Geel, 2001). One of the most frequently reported algal palynomorph is the chlorophyte genus *Pediastrum* Meyen (Burden et al. 1986; Zippi et al. 1990), with its flat, star-shaped colonies (coenobia) (Jankovska & Komarek, 2000; Turner et al. 2014). They are usually associated with eutrophic conditions (Shubert, 2003), although a few taxa such as *Pediastrum integrum*, prefer oligotrophic environments (**Table 3.1**). Another commonly studied colonial chlorophyte alga is the genus *Botryococcus* Kützing, with densely-packed cone-shaped cells radiating from the center of a mostly spherical colony (van Geel, 2001). The response of *Botryococcus* ("pond scum") to the trophic state of water bodies has been reported in many studies (e.g., Guy-Ohlson, 1992; Kuhry, 1997; Jankovska & Komarek, 2000; Smittenberg et al. 2005; Medeanic, 2010; Levine et al. 2012; Garel et al. 2013). The cysts of freshwater dinoflagellates, notably the genera *Peridinium* Ehrenberg and *Parvodinium* Carty, have been shown to be useful proxies of human impact (Burden et al. 1986; McCarthy et al. 2011; McCarthy & Krueger, 2013; Drljepan et al. 2014; Krueger & McCarthy, 2016) as well as natural eutrophication (Drljepan et al. 2014) and acidification

(Zippi et al. 1990 & 1991) in North American lakes. Studies like that of Burden et al. (1986) demonstrate the greater sensitivity of NPP compared to pollen and spores, particularly (in this case) with regard to Native American (Wendat) impact. Whereas early-European impact can be identified by an increase in *Ambrosia* pollen (referred to as the *Ambrosia* or ragweed rise/ zone) caused by land clearing activities, Wendat impact is most easily identified by observing changes in the NPP (dinoflagellate cysts and *Pediastrum*) record. The response of the lake to agricultural activities in the Wendat zone is similar to early-European/ lower ragweed zone (see **Chapters 1** & **4** for more information).

The chief advantage of NPP over other paleolimnological indicators is their presence in samples prepared for pollen analysis, although common techniques like acetolysis have been shown to selectively destroy some palynomorphs, notably desmids (see **Chapter 2**, Riddick et al. 2016). The high preservation potential of these organic-walled microfossils gives them an advantage over mineralized microfossils. For example, low abundance prohibited diatom studies in sediment deposited prior to the mid-nineteenth century in the main basin of Lake Simcoe (Hawryshyn, 2010), whereas organic-walled microfossils such as chironomids (**Figure 3.1**) are common to abundant (Rodé, 2009).

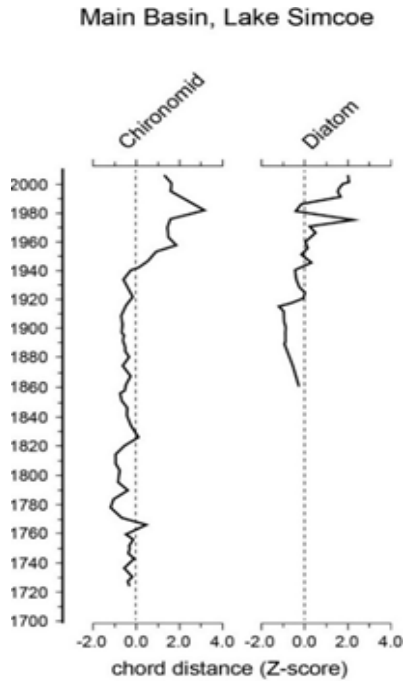

Figure 3.1: Chironomid- and diatom-based paleolimnological analyses in a ^{210}Pb-dated profundal sediment core collected in 2007 from the main basin of Lake Simcoe. The rate of chironomid and diatom community change, expressed as Z-scores of chord distance around the vertical dashed line that represents mean rate of change for the dataset (Z-score = 0), is greatest at times of perturbation (modified from North et al. 2013; chironomid data from Rodé, 2009; diatom data from Hawryschyn, 2010). Perturbation can be linked with anthropogenic impact on the lake, such as large-scale European colonization in the mid-nineteenth century, canal construction for the draining of the Holland Marsh in the 1920s, and urbanization associated with the post-WWII population boom in the watershed.

Volik et al. (2016) found a relatively rich assemblage of algal palynomorphs (e.g., *Botryocccus*, *Pediastrum* spp. and various desmid species) in sediments deposited in the main basin of Lake Simcoe since deglaciation (**Figure 3.2a**). Intervals of drought (**Figure 3.2b** and identified by stippling in **Figure 3.2a**), are associated with sharp declines in NPP and testate amoeba diversity. Changes attributed to anthropogenic impact (assemblage NPP-4 attributed to Euro-Canadians, and the upper part of NPP-3 tentatively attributed to the Wendat) are discussed later in this chapter.

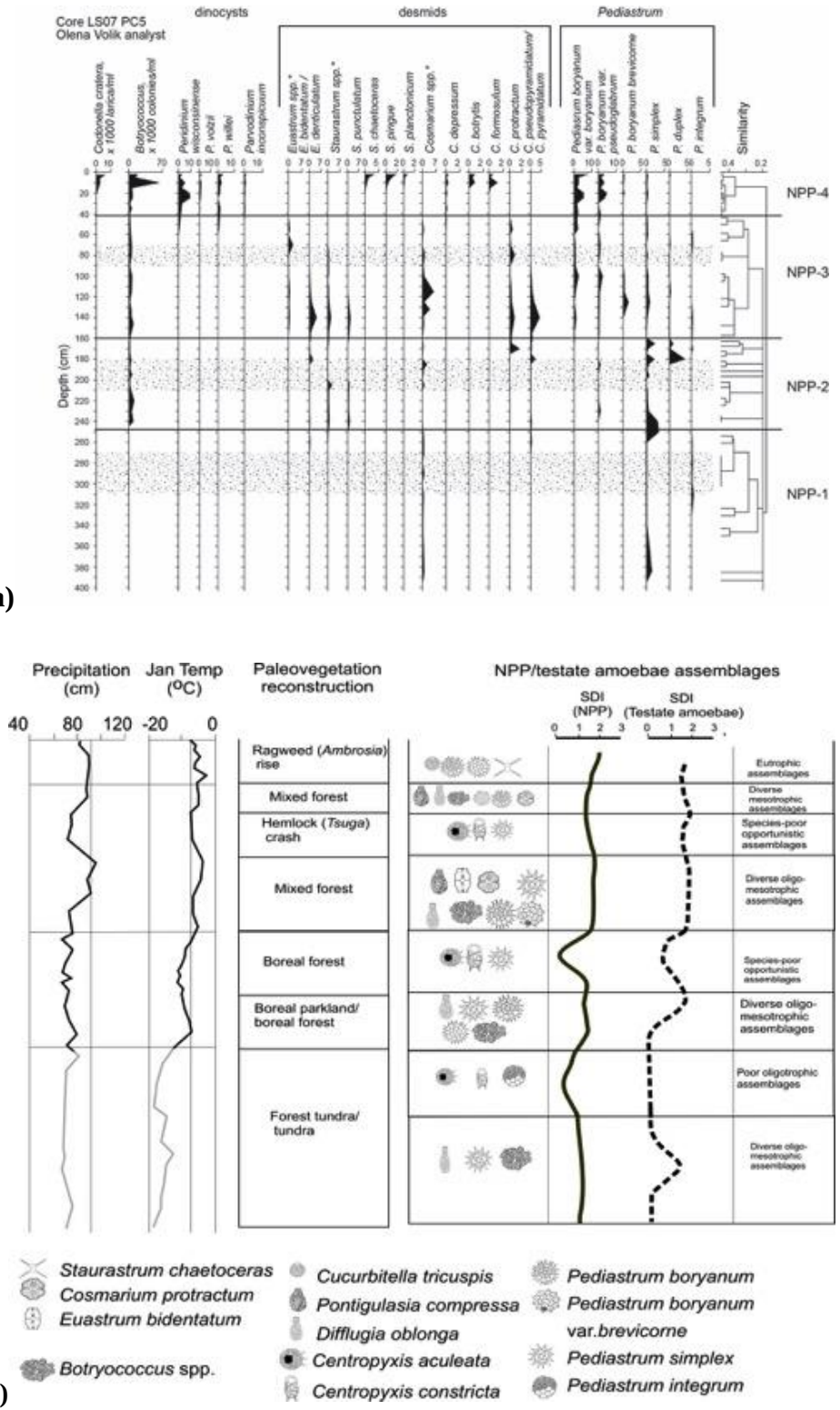

Figure 3.2: a) Non-pollen palynomorphs were present throughout core LS07 PC5 from the main basin of Lake Simcoe, with sparse, low-diversity assemblages characterizing glacial Lake Algonquin sediments below 250 cm. **b)** NPP diversity, measured by the Shannon Diversity Index (SDI: Shannon & Weaver, 1964) appears to be controlled by climatic parameters, reconstructed from pollen profiles using the transfer functions of Bartlein and Whitlock (1993): warm, moist conditions are associated with high diversity whereas cold, dry conditions appear to have produced sparse, low-diversity assemblages. The sharp decline

in both NPP and testate amoeba diversity coincides with the early Holocene drought that produced slightly brackish conditions in nearby Georgian Bay (McCarthy & McAndrews, 2012; McCarthy et al. 2012). Reproduced from Volik et al. (2016).

3.1.1 Lake Simcoe

Lake Simcoe is the largest lake in Ontario after the Laurentian Great Lakes, with a surface area of 722 km^2, mean water depth of 16 m, and approximate volume of 11 x 10^9 m^3 (Winter et al. 2007). The Lake Simcoe watershed is being rapidly developed, with undisturbed forests (mixed forest of zone L1 of Rowe, 1972) occupying only about 11% of its 3,576 km^2-area (Johnson, 1997). Most of the urbanization is in the western and southern parts of the watershed, with the cities of Barrie, Newmarket and Aurora making up the largest portion.

More than 60% of the total drainage is accounted for by five of the 35 tributary streams draining into the lake from the south and east (LSRCA, 2003). Drainage from the heavily populated watershed of the East and West Holland Rivers that flow through the drained Holland Marsh, the "market garden of Ontario", contributes high nutrient flux which is reflected in modern biomass (North et al. 2013) (**Figure 3.3**). The major outflow for the lake is to the north, into Lake Couchiching and ultimately to Georgian Bay/ Lake Huron via the Severn River. The prevailing winds are from northwest (1^{st}) and southwest (2^{nd}). The frequency of southwesterly winds increases in summer months (Environment Canada, 2003).

Euro-Canadian impact on the lake and surrounding areas extends back to the 1790s with the establishment of York County by Governor John Graves Simcoe and the construction of Yonge Street (Highway 11) from Toronto to Lake Simcoe (see **Appendix D**). Built over Iroquois trails, this road was integral to the planning of Upper Canada (LSRCA, 2000; Danesh et al. 2013). Widespread settlement of the eastern Lake Simcoe watershed followed, most markedly after completion of the Ontario, Simcoe and Huron Railway in this region, and the end of WWII brought about a second major population increase: the populations of Newmarket and Aurora rose from ~600 to ~3,350 between 1841 and 1871, and from ~6,750 to ~32,550 between 1941 and 1971 (LSRCA, 2000; Danesh et al. 2013). Cultural eutrophication contributing ~70% phosphorus loading into the lake (OMOE,

2010) has impacted water quality in Lake Simcoe, causing total phosphorous (TP) driven algal blooms (Johnson & Nicholls, 1989; Eimers et al. 2005; LSEMS, 2008; LSRCA, 2009; LSPP, 2009; Hiriart-Baer et al. 2011; North et al. 2013). Beginning in the 1970s, water quality issues resulted in problems such as beach closures and drinking water contamination (Evans et al. 1996; Winter et al. 2002; Danesh et al. 2013). In the 1980s the identification of environmentally significant areas, phosphorus sources and phosphorus reduction became important goals of the Lake Simcoe Environmental Management Strategy (LSEMS). The background, pre-European, TP loading into the lake was ~32 tonnes/ year, compared to the current 72 tonnes of TP loading that occur in the lake each year (LSRCA, 2009; Danesh et al. 2013). In 1986, the conservation authority responsible for the lake was renamed the Lake Simcoe Region Conservation Authority (LSRCA) and by 2000 an estimated 16.5 tonnes of phosphorus was diverted from the lake (LSRCA, 2015).

High biochemical/ biological oxygen demand (BOD) and sedimentary oxygen demand has resulted in the depletion of dissolved oxygen (DO) concentrations, stressing cold-water fish like lake trout and whitefish, which are an important part of the region's economy (Winter et al. 2007; Palmer et al. 2011). A report by the Ministry of the Environment and Climate Change (MOECC) on Lake Simcoe (*'Minister's Five Year Report on Lake Simcoe: To protect and restore the ecological health of the Lake Simcoe watershed'*) states that the optimal concentration of DO (and their target level) for supporting a sustainable cold-water fish community is 7 mg/L. Measurements of end of summer deep water DO from Kempenfelt Bay (between Cook's Bay and Smith's Bay) indicates a trend of increasing DO concentrations between 1980 and 2012, but levels remain below 7 mg/l (except in 2005). Additionally, the report shows evidence of cold-water fish recovery over the three decades, but DO concentrations remain below target levels so fish communities are still stressed (MOECC, 2016). As a result, the popular cold-water fishery that generates over $200 million per year (Young et al. 2010), has been sustained in recent years only because stocks of fish are added each season (OMOE, 2010).

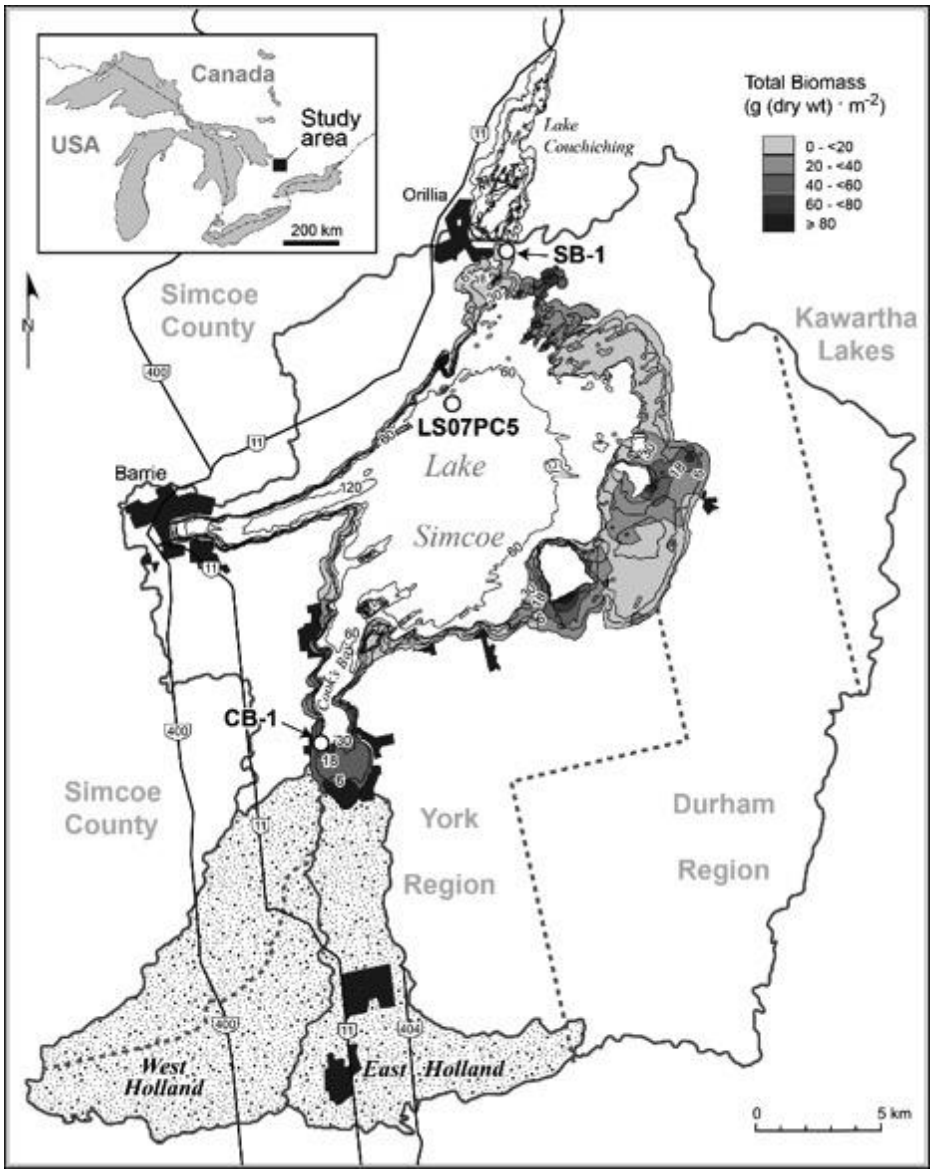

Figure 3.3: Lake Simcoe biomass (adapted from North et al. 2013), highlighting the West & East Holland sub-watersheds (stippled) that are a main source of nutrients, discharging into Cook's Bay (location of core CB-1), where total phosphorus (TP) concentrations are the highest. This relatively small, shallow bay receives ~22% of Lake Simcoe TP loads (LSRCA, 2007, 2009). Southwesterly winds are common in summer months (when productivity is highest), transporting nutrients and sediments to the north and east basins of the lake. This would contribute to the high productivity and biomass in the eastern part of the lake.

3.1.2 NPP as Tools in the Management of Water Quality in Lake Simcoe

The management of eutrophication and restoration of a lake and its watershed requires an understanding of long-term changes in lake nutrient levels (Schindler, 2006; Smol, 2010), not just synoptic measurements of biomass or nutrient concentrations in the water column. The use of sedimentary phosphorus concentrations to infer the history of

nutrient flux (Hiriart-Baer et al. 2011) has been called into question (Ginn et al. 2012), illustrating the need for other proxies of eutrophication in sediment cores. The fossil remains of aquatic organisms (e.g., algae) are useful biomonitors, not only of nutrient loading, but also siltation and heavy metal flux resulting from land-clearing for agriculture, urbanization and industrialization (e.g., Hall & Smol, 1996; Smol, 2010; Haas, 2010; Mudie et al. 2011).

The most commonly used algae in paleolimnological reconstruction are diatoms, whose response to anthropogenic impact has been well-documented (Round et al. 1990; Reavie & Smol, 2001; Ekdahl et al. 2007; Smol & Stoermer, 2010). Hawryshyn et al. (2012) identified synchronous diatom assemblage shifts in four cores from different parts of Lake Simcoe, which they attributed to anthropogenic impact and climate warming, particularly in the mid- to late-twentieth century. These correlate well with rapid changes in chironomid communities in the 1920s, 1950s and late 1970s, attributed by Rodé (2009) to canal construction for the draining of the Holland Marsh and rapid urbanization in the watershed (**Figure 3.1**). More recently, testate amoebae (also known as thecamoebians, testate rhizopods or arcellaceans) have been shown to be sensitive to cultural eutrophication (Reinhardt et al. 2005; Roe et al. 2010; Patterson et al. 2012; Drljepan et al. 2014) as well as contamination from mining activities (Kauplilla et al. 2006; Neville et al. 2011; Kihlman and Kaupilla, 2012; Patterson et al. 2013). Transfer functions have even been developed to relate testate amoeba (thecamoebian) assemblages to concentrations of sedimentary phosphorus in lakes (Patterson et al. 2012).

Danesh et al. (2011) found an increase in difflugiid taxa, particularly *Cucurbitella tricuspis*, and the tintinnid ciliate, *Codonella cratera*, associated with the sharp increase in nitrites (NO_2), nitrates (NO_3) and TP associated with Euro-Canadian agriculture, beginning in the mid-nineteenth century (**Figure 3.4**). *Codonella cratera* has been shown to respond to increases in human population and industry (Limon et al. 1983; Barbieri & Orlandi, 1989; Kling, 2005; Danesh et al. 2013; Drljepan et al. 2014). *Cucurbitella tricuspis* thrives in response to increases in nutrient concentrations (Roe et al. 2010; Patterson et al. 2012) and low DO because of a pseudoplanktonic phase associated with mats of floating *Spirogyra* (Neville et al. 2011; Danesh et al. 2013; Drljepan et al. 2014).

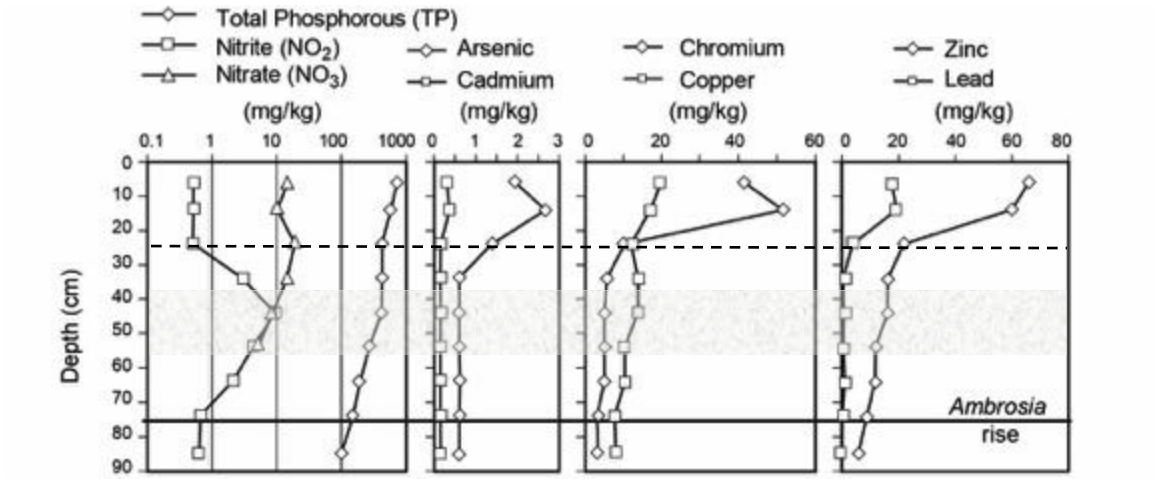

Figure 3.4: Nutrient & heavy metal analysis scaled by depth from the Cook's Bay core (CB-1) (adapted from Danesh, 2011; Danesh et al. 2013). The *Ambrosia* (ragweed) rise, identified from the pollen assemblage between 80 and 70 cm in core CB-1 using constrained cluster analysis (CONISS) has been dated ca. 1840 in a core from Wye Marsh, Midland (Chittenden, 1990). The stippled area represents the draining of the Holland Marshes in the late 1920s – 1930s. The dashed line represents the beginning of the post WWII population boom and increased urbanization.

Desmids, unicellular conjugate charophyte algae, have been shown to be sensitive biomonitors in limnological studies, reflecting changes in contamination, pH, and trophic status of water bodies (Coesel, 1984, 2003; Borics et al. 1998; Fehér, 2003; Krasznai et al. 2008). Their surfaces can be quite complex with granules, grooves and specula that create distinct patterns (Taft, 1945). Most species are benthic and prefer oligotrophic to mesotrophic environments, but some species are planktonic and some prefer eutrophic conditions (**Table 3.1**). They are rarely mentioned in palynological or paleolimnological studies because they are normally destroyed when acetolysis is carried out on a sample (**Chapter 2**, Riddick et al. 2016). This would explain their abundance in unacetolysed pollen preparations from Lake Simcoe (Danesh et al. 2013; Volik, 2014; Riddick et al. 2016; Volik et al. 2016). Other concerns regarding the use of acetolysis include the destruction of dinoflagellate cyst families Polykrikaceae and Protoperidiniaceae, thin-walled microfossils and non-sporopollenin pollen components (Reid, 1977; Marret, 1993; Mudie & McCarthy, 2006; Hesse & Waha, 1989).

Table 3.1: Ecology of desmids (*Cosmarium*, *Euastrum* and *Staurastrum*), *Pediastrum* spp. (light grey) *Botryococcus* spp. (medium grey) and dinoflagellate spp. (*Peridinium* and *Parvodinium* spp.- dark grey shading) identified in sediment cores from Lake Simcoe, primarily based on Jankovska & Komarek (2000), Komarek & Jankovska (2001) and Štastný (2010).

Trophic state of habitat	Species	Life habit	Acidity
Eutrophic	*Cosmarium protractum* (Nägeli) De Bary	Benthic	Alkaline
	Staurastrum chaetoceras (Schröder) G.M.Smith	Planktonic	Alkaline
	Pediastrum boryanum var. boryanum (Turpin) Meneghini	Planktonic	Alkaline
	Pediastrum boryanum var. pseudoglabrum Parra.		
Mesotrophic-Eutrophic	*Cosmarium botrytis* Ralfs	Benthic	Acidic-Neutral
	Cosmarium granatum Ralfs		
	Cosmarium punctulatum Bréb		Acidic-Alkaline
	Cosmarium reniforme (Ralfs) W.Archer		
	Cosmarium formosulum Hoff	Benthic-Planktonic	Acidic-Alkaline
	Staurastrum pingue Teiling	Planktonic	Alkaline
	Staurastrum planctonicum Teiling		Alkaline-Neutral
	Pediastrum boryanum var. brevicorne Braun	Planktonic	Alkaline
	Pediastrum simplex var. simplex Meyen		Alkaline-Neutral
	Pediastrum duplex var. duplex Meyen		Unknown
	Botryococcus brauniiKützing	Planktonic	Alkaline-Neutral
	Parvodinium inconspicuum (Lemmermann) Carty	Planktonic	Acidic-Alkaline
	Peridinium volzii Lemmermann		
	Peridinium willei Huitfeld Kaas		
Mesotrophic	*Cosmarium depressum* (Nägeli) P.Lundell	Benthic	Alkaline-Neutral
	Cosmarium variolatum P.Lundell		Acidic
	Cosmarium subcucumis Schmidle		
	Cosmarium subcrenatum Hantzsch	Benthic-Atmophytic	Acidic
	Staurastrum sebaldi Reinsch	Benthic	Acidic
	Euastrum bidentatum Nägel	Benthic	Acidic-Neutral
	Euastrum denticulatum F.Gay		Acidic
	Peridinium wisconsinense Eddy	Planktonic	Acidic-Alkaline
Mesotrophic-Oligotrophic	*Cosmarium pseudopyramidatum* P.Lundell	Benthic	Acidic
	Cosmarium pyramidatum Ralfs		
	Euastrum luetkemuelleri F.Ducell	Benthic	Acidic
Oligotrophic	*Staurastrum punctulatum* Ralfs	Benthic	Acidic
	Pediastrum integrum Nägeli	Unknown	Unknown

Danesh et al. (2013) showed that NPP assemblages in a core from the southern part of Lake Simcoe (Cook's Bay core CB-1) responded to initial settlement of York County in the mid-nineteenth century, the draining of the Holland Marsh in the early-twentieth century and to rapid urbanization in the watershed since the 1950s. With each phase of development, a reduction in desmid abundance and increase in dinoflagellate cyst abundance was observed. Phytolith abundance peaked slightly with the draining of the Holland Marsh, with the greatest increase in abundance responding to the post-WWII

population boom. The highest abundance of *Pediastrum* and almost all *Codonella cratera* occur after the post-WWII population boom (**Figure 3.4**).

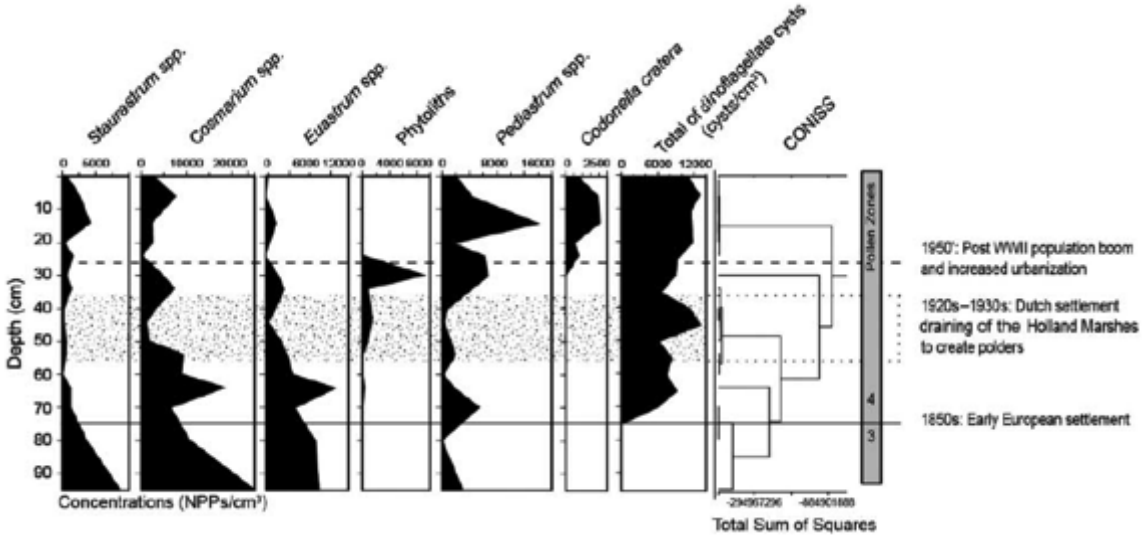

Figure 3.5: NPP assemblage from Cook's Bay core (CB-1). At the transition between pollen zones 3 and 4, associated with a rise in *Ambrosia* (Ragweed) pollen, marks early-European settlement (solid line). The stippled area represents the draining of the Holland Marshes. The dashed line represents the beginning of the post WWII population boom and increased urbanization. The abundance of phytoliths increase during the draining of the Holland Marsh and are at their highest around the beginning of the post-war boom (Danesh et al. 2013).

Volik et al. (2016) interpreted testate amoeba and NPP data in a core from the main basin (LS07 PC5; **Figure. 3.6**) as recording pre-European eutrophication and siltation/ turbidity. This is characterised by higher concentrations of difflugiid testate amoebae (including *Cucurbitella tricuspis*), the appearance of dinoflagellate cysts, loss of benthic desmids (e.g., *Euastrum* spp.) and oligotrophic *Pediastrum integrum*, reflecting meso-eutrophic conditions. The increase in nutrient availability below the ragweed rise was tentatively attributed to the Wendat/ Huron who occupied the region between Lake Simcoe and Georgian Bay (Lake Huron) known as Wendake (Huronia) until ca. 1650, when they were defeated and dispersed by the Iroquois (Birch & Williamson, 2015). The decline in testate amoeba and NPP concentrations immediately above the ragweed rise records higher sedimentation rates attributed to land clearing by European settlers, and the near-absence of benthic desmids such as *Cosmarium* and *Euastrum* spp. (**Table 3.1**) between 15 and 60 cm records the accompanying turbidity. In the upper 15 cm of the core there is an increase in predominantly planktonic taxa characteristic of eutrophic waters, including the desmids *Staurastrum pingue* and *S. chaetoceras*, cysts of

Peridiniium willei and *P. volzii*, colonies of *Botryococcus* and lorica of the tintinnid ciliate *Codonella cratera*. These changes were attributed to urbanization and industrialization in the Lake Simcoe watershed beginning in the 1950s (**Figure 3.6**). The dominance of planktonic NPP in the upper 15 cm records low DO in bottom waters associated with increased BOD (Volik et al. 2016). Low DO levels in the main basin are consistent with findings by Winter et al. (2007), Palmer et al. (2011) and MOECC (2016).

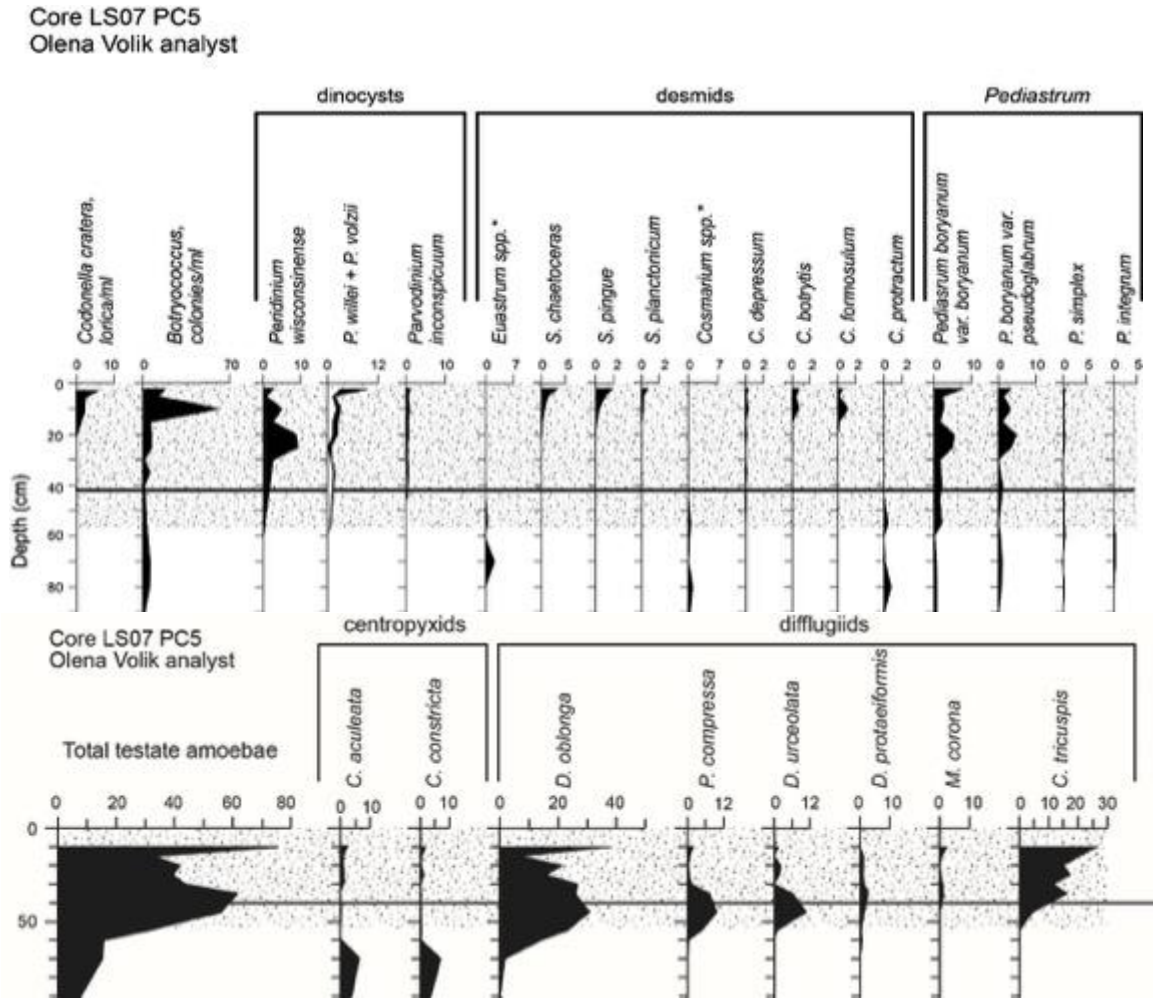

Figure 3.6: a) Non-pollen palynomorph (NPP) and **b)** testate amoeba assemblages from the main basin core LS07 PC5 recording eutrophication attributed to human impact (stippled) beginning prior to the *Ambrosia* (ragweed) rise (thick line ~40 cm), tentatively attributed to the Wendat. The decline in testate amoeba and NPP concentrations immediately above the ragweed rise records higher sedimentation rates attributed to land clearing by European settlers, and the near absence of benthic desmids (most *Cosmarium* and *Euastrum* spp.) between 15 and 60 cm records the accompanying turbidity. The dominance of planktonic NPP in the upper 15 cm records low DO in bottom waters associated with increased BOD (modified from Volik, 2014 and Volik et al. 2016).

Riddick et al. (2016) noted that the concentrations of nitrate, nitrite, copper, chromium and zinc around 60 cm were similar to the increase in nitrate, cadmium, zinc and lead around the ragweed rise ~25 cm higher in core SB-2 from Smith's Bay in northern Lake Simcoe (**Figure 3.7**). This was tentatively attributed to human activities prior to early-European settlement.

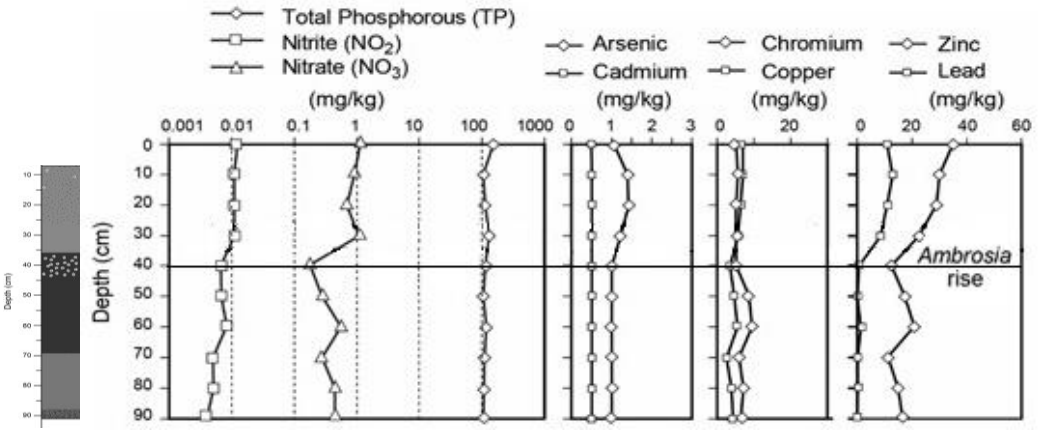

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Figure 3.7: Nutrient & heavy metal analysis of marly sediments scaled by depth from Smith's Bay core (SB-2) (modified from Riddick et al. 2016). Increases in nutrients, centered at 60 cm and above 40 cm, correspond with decreases in desmid abundance in SB-1, believed to be caused by human activities (Native American and Euro-Canadian settlement respectively). See description of core lithology in **Appendix B**.

3.2 This Study

The aim of this study is twofold: 1) to present and interpret the NPP record of the last several centuries in cores from Smith's Bay in order to assess the response to human impact on the Lake Simcoe watershed since the sharp rise in ragweed pollen marking Euro-Canadian settlement of the region beginning in the mid nineteenth century, and 2) to examine the spatial and temporal distribution of several main groups of NPP, primarily algae, down-core through the *Ambrosia* (ragweed) zone in three cores from different parts of Lake Simcoe to investigate evidence of pre-colonial siltation and eutrophication indicative of land disturbance. Comparing the NPP record from all three locations (plus nutrient and heavy metal analysis from two locations) should highlight the paleolimnological value of NPP in tracking historic and geographic variations of human impact on this large lake (Van Geel, 2006; Haas, 2010).

3.3 Methods

3.3.1 Coring & Subsampling

In October, 2012, core SB-1 was collected from Smith's Bay, in northern part of Lake Simcoe near Lake Couchiching, through which Lake Simcoe drains into the Great Lakes via the Severn River into Georgian Bay. This 80 cm-long sediment core was collected at a water depth of 2.15 m (44°35'53.76"N - 79°22'37.87"W) using a Rowley Dahl sampler and analysed for NPP and testate protozoans. Volik (2014) reported on the NPP and testate amoeba assemblage from the upper 45 cm of core SB-1 and Riddick et al. (2016) reported on desmid assemblages prior to and following acetolysis treatment as well as a summary of other NPP and testate amoeba data throughout the core.

In April, 2014, a second Rowley Dahl core was collected from Smith's Bay (~44°36'10.02"N - 79°22'57.07"W), at ~2 m water depth. The 90 cm-long core SB-2 was initially collected for nutrient and heavy metal analysis (Riddick et al. 2016), but the discovery of anomalously high concentrations of heavy metals and nutrients below the *Ambrosia* rise led to subsequent analysis of algal palynomorphs and their ecological preferences and tolerances (**this chapter**), and of pollen, and fungal palynomorphs and micro-charcoal to assess the provenance of this anomaly (**Chapter 4**).

3.3.2 Geochemical Analysis

Analysis of nitrate, nitrite, TP, and heavy metals from core SB-2 followed procedures described in the 'Standard Methods for the Analysis of Water and Wastewater' (Rice et al. 2012) using a Thermo-Fisher iCAP 6300 ICP Spectrometer. Sediment samples of 2 cm^3 volume were analyzed for nutrients and heavy metals by E3 Laboratories, a Canadian Association for Laboratory Accreditation (CALA) certified laboratory.

3.3.3 Palynological Processing

Palynological processing of sediments from core SB-1 (by Olena Volik and Nicholas Riddick) employed standard maceration techniques for Quaternary sediments (modified from Faegri & Iversen, 1975), including hydrochloric acid (HCl) and hydrofluoric acid (HF) to dissolve mineral sediments and spiking with a known quantity of *Lycopodium clavatum* spores (10,850 +/-200 spores) (Stockmarr, 1971). Importantly, however,

samples were not initially acetolysed because oxidation-susceptible palynomorphs (notably desmids) are destroyed by this common treatment (**Chapter 2**, Riddick et al. 2016). Subsequent acetolysis (by Nicholas Riddick) removed much of the organic matter (including most of the desmids), but made analysis of pollen and acetolysis-resistant NPP (e.g., fungal spores) easier to accomplish. Palynological analysis of samples from core SB-1 (algal NPP by Olena Volik and Nicholas Riddick, arboreal pollen (AP) by Olena Volik and reanalysis of non-arboreal pollen (NAP) by Nicholas Riddick) was completed using a Leica DMLB light microscope at 400X magnification. A number of sources were used to identify these microfossils, including, McAndrews et al. (1973), Beyens & Meisterfeld (2001), John et al. (2002), Wehr & Sheath (2003), Coesel & Meesters (2007), Komárek & Jankovská (2001), Kramer et al. (2010) and Mudie et al. (2010).

3.4 Results

3.4.1 Algal palynomorphs from core SB-1, Smith's Bay

Desmids are well-preserved and relatively abundant in core SB-1, except in the samples from 65, 60 and 50 cm and 25 and 20 cm where they range from ~3,000 – ~16,000 half-cells/ ml sediment, compared to the average ~40,000 half-cells/ ml (**Figure 3.8**). The highest abundances (exceeding 100,000 half-cells/ ml sediment) are in the upper 15 cm of the core. Associated with the ragweed rise between 25 and 30 cm in core SB-1, the desmid assemblage transitions from one dominated by the oligotrophic- mesotrophic taxa *Cosmarium pyramidatum/ C. pseudopyramidatum* to a more diverse assemblage rich in meso-eutrophic and eutrophic (primarily planktonic) taxa like *Cosmarium botrytis, C. reniforme/ C. formosulum, C. protractum*, *Staurastrum chaetoceras* and *S. pingue/ S. planctonicum* and the mesotrophic *C. depressum* (see **Table 3.1** for ecological preferences). The oligotrophic *Staurastrum punctulatum*, the meso-oligotrophic *Euastrum luetkemuelleri*, the mesotrophic *C. variolatum/ C. subcucumis/ C. subcrenatum* and *Staurastrum sebaldi* (as well as *Cosmarium franzstonii* whose ecology has not been ascertained), are also characteristic of the assemblage below the ragweed rise.

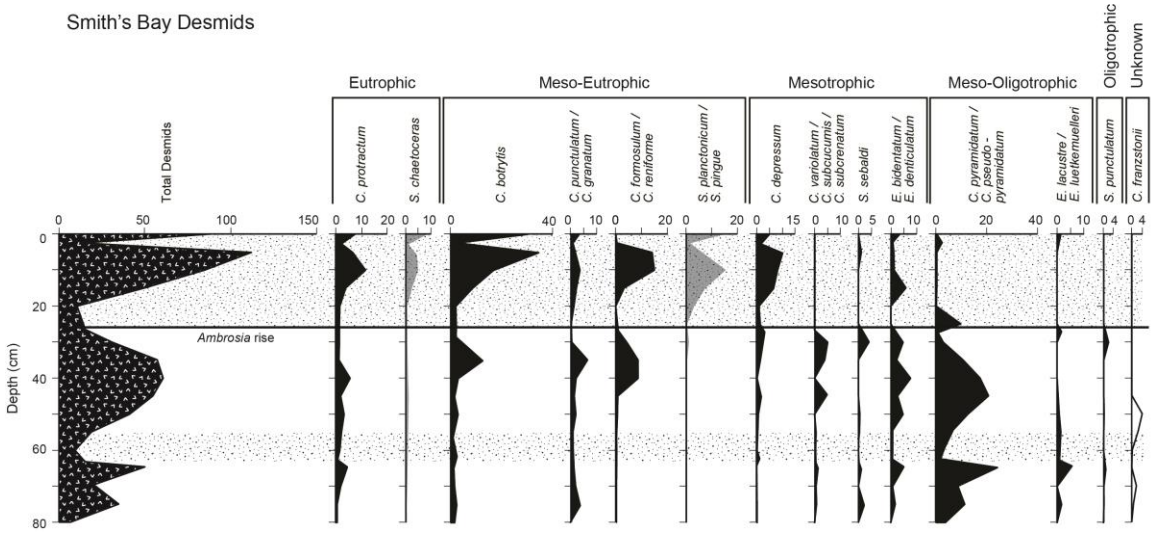

Figure 3.8: Desmid assemblage (x1000 half-cells/mL) from Smith's Bay core SB-1 (modified from Riddick et al. 2016) with trophic preferences and life habit from sources listed in **Table 3.1** (planktonic taxa in grey, benthic in black). Decreases in benthic desmid abundance (from 55- 65 cm and 35-20 cm) are associated with increased siltation and associated turbidity from land disturbance. Stippling highlights intervals attributed to human impact.

Concentrations of *Pediastrum* coenobia are lower than those of desmid half-cells, but less variable, ranging from ~400 – ~8,000 coenobia/ ml. They first exceed 1,000 coenobia/ ml sediment in the sample from 65 cm and peak at ~8,000 coenobia/ ml in the sample from 5 cm. As with the desmids, there is a marked decline in abundance around the ragweed rise, when a shift from an assemblage relatively rich in the meso-eutrophic *Pediastrum simplex var. simplex* and oligotrophic *P. integrum* to one dominated by the eutrophic *Pediastrum boryanum var pseudoglabrum* and *P. boryanum var boryanum* (**Figure 3.9**).

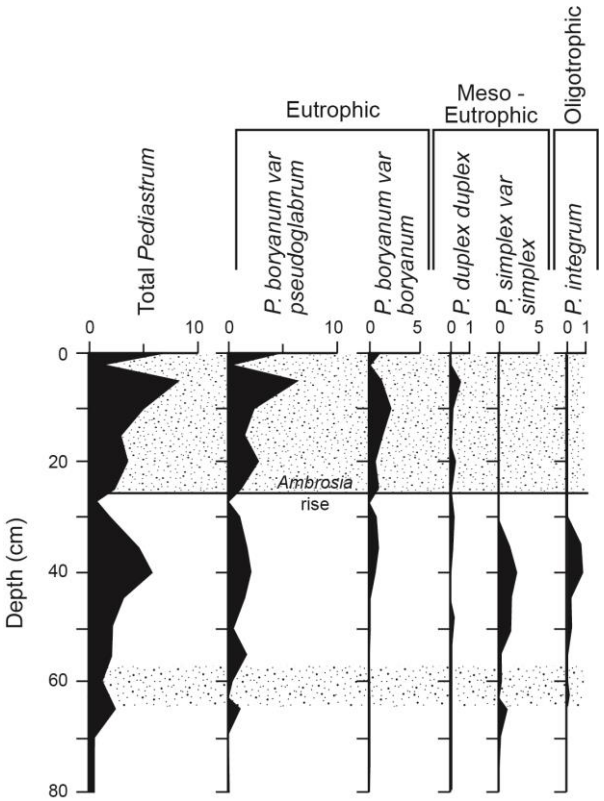

Figure 3.9: *Pediastrum* assemblage (x1000 coenobia/ mL) from Smith's Bay core SB-1. Stippling highlights intervals of eutrophication and turbidity, attributed to human impact on the watershed. The decrease in *Pediastrum* abundance and increase in relative abundance of eutrophic taxa at the expense of oligotrophic taxa at 40 cm, just before *Ambrosia*/ ragweed rise (black line) corresponds well with decreases in desmid abundance (**Figure 3.8**).

Arboreal pollen (AP) and reanalysed non-arboreal pollen (NAP) results from core SB-1 are presented in **Figure 3.10**. NAP, notably *Ambrosia*, begins to increase around 25-30 cm and *Helianthus* is present at 60 and 63 cm.

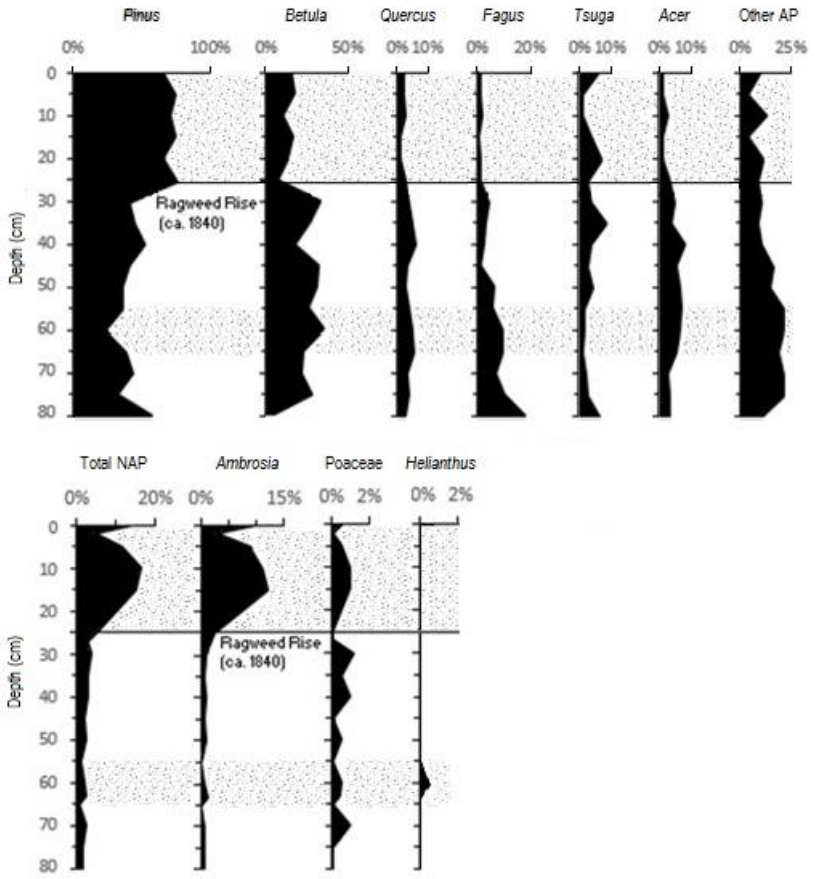

Figure 3.10: Pollen (AP & NAP) results (relative abundance) from Smith's Bay (SB-1). Reanalysis of NAP indicate that the *Ambrosia* (ragweed rise) is slightly higher than identified in **Chapter 2** (Riddick et al. 2016), now placed at 26 cm. The increase in ragweed is a regional pollen marker, dated to ca. 1840 (Chittenden, 1990; McAndrews, 1994). The pre-European zone (between 65 and 55 cm) is characterized by the presence of the cultivar/cultivar pathogen *Helianthus* (sunflower). A minimum of 200 pollen grains were counted to quantify NAP.

3.4.2 Detailed Algal Palynomorph Data from Core CB-1, Cook's Bay

The algal palynomorph assemblage prior the ragweed rise (~75 cm) is characterised by an absence of *Botryococcus* colonies and dinoflagellate cysts, low *Pediastrum* abundance (~10,000 coenobia/ mL) (primarily *Pediastrum integrum*) and high desmid abundance (~110,000 half-cells/ mL) (primary *Cosmarium* and *Euastrum*). After the ragweed rise, the *Pediastrum* assemblage shifts, reflecting a more eutrophic environment with *P. integrum* abundances decreasing and *P. boryanum var boryanum* and *P. boryanum var pseudoglabrum* becoming dominant. *Botryococcus* colonies and dinoflagellate cysts are present after the ragweed rise, recording meso-eutrophic conditions, while desmid abundance remains low; their assemblage is dominated by meso-eutrophic varieties (e.g., *Staurastrum chaetoceras*, *Cosmarium botrytis* and *C. depressum*) (**Figure 3.11**).

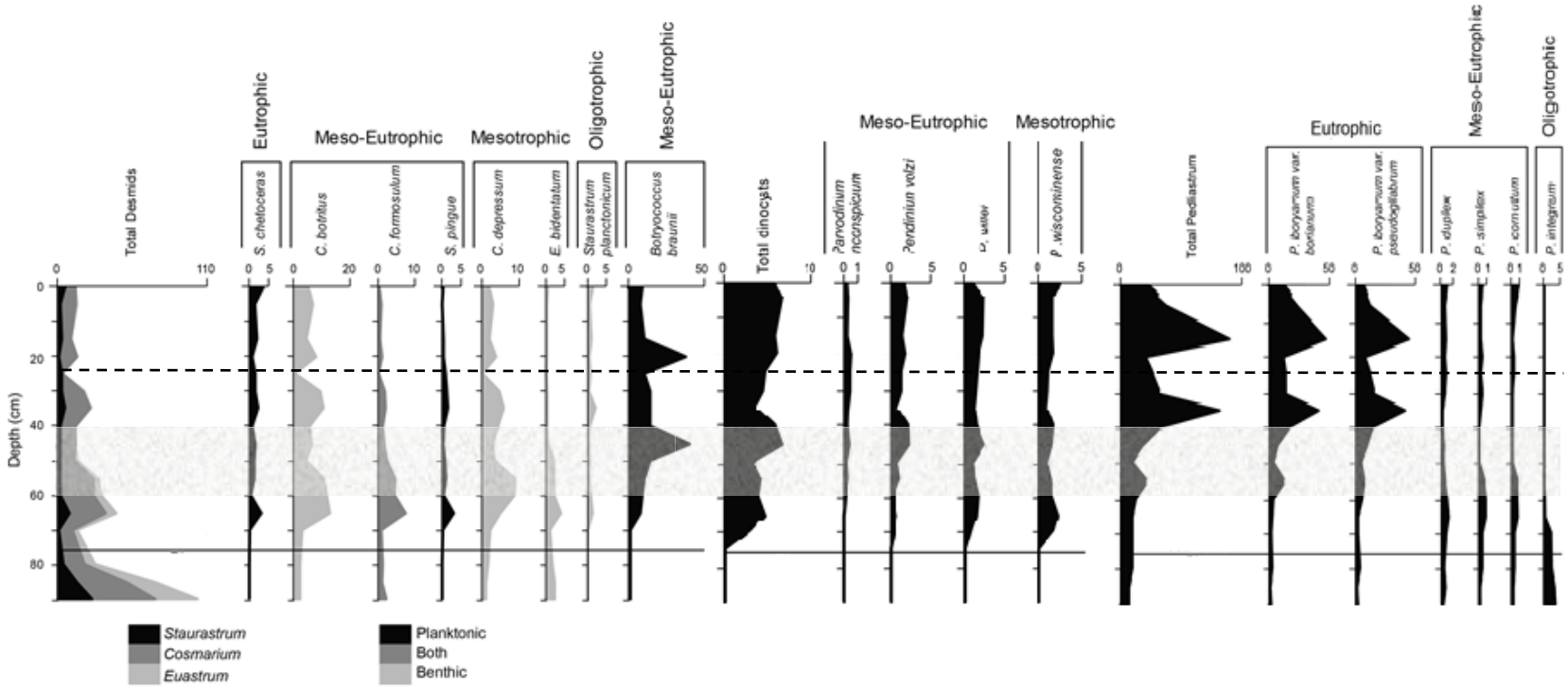

Figure 3.11: Non-pollen palynomorph (NPP x1000) assemblages from Cook's Bay core CB-1, organised according to trophic preferences and life habit using sources listed in **Table 3.1**. Euro-Canadian impact is observed in several stages, including early-European settlement and agriculture (indicated by the ragweed rise – solid black line), the draining of the Holland marsh (stippled area) and post-WWII population increase and industrialization (beginning at the dashed black line). Desmid abundance initially decreases with each impact. *Botryococcus* and dinoflagellate cysts appear around the ragweed rise, with *Botryococcus* peaks associated with the draining of the marsh and the post-war boom. *Pediastrum* abundance peaks similarly to *Botryococcus*, though later in both cases. Overall, Euro-Canadian impact causes a shift in the NPP assemblage reflecting a more eutrophic and turbid environment with more planktonic taxa (some desmids, *Pediastrum, Botryococcus* and dinoflagellate cysts) are present (modified from Volik, 2014). Impact stages are identified using constrained cluster analysis (CONISS), completed by Danesh et al. (2013).

3.5 Discussion

The increase in relative abundance of ragweed and other NAP is a regional pollen marker of land disturbance (McAndrews, 1994), the age for which has been estimated around 1840 CE in a core from the nearby Wye Marsh (Chittenden, 1990). This date is consistent with the historic evidence of European settlement of the region between Lake Simcoe and Georgian Bay. The first stage of the Ontario, Simcoe and Huron Union Railroad Company opened in May 1853 with steam train service between Toronto and Aurora (at that time called Machell's Corners). The rail line reached Collingwood in June 1855 (Railway Pages, 2014), linking the Upper and Lower Great Lakes.

Similar to other sites in the lower Great Lakes region, like Crawford Lake (e.g., McCarthy & Krueger, 2013; Krueger & McCarthy, 2016) and Awenda Provincial Park (Burden et al. 1986), the algal palynomorph assemblage in sediments from western Lake Simcoe that are rich in ragweed pollen differ from underlying sediments. These changes are consistent with siltation and eutrophication associated with European land clearing and agriculture beginning in the mid-nineteenth century and urbanization in the Lake Simcoe watershed in the latter half of the twentieth century.

The NPP assemblage in the upper 15 cm in core SB-1 from Smith's Bay, is characterized by meso-eutrophic to eutrophic algal palynomorphs, many of which are planktonic (e.g., *Staurastrum chaetoceras, S. planctonicum*/ *S. pingue* and *Pediastrum,* primarily *P. boryanum var pseudoglabrum* – **Figures 3.8** & **3.9**). Unlike sediments from the main basin and Cook's Bay, other planktonic algal palynomorphs, such as dinoflagellate cysts and *Botryococcus* colonies appear infrequently, while the planktonic tintinnid ciliate *Codonella cratera* is absent altogether. This, combined with higher abundances of benthic desmids (e.g., *Cosmarium botrytis*) suggests higher levels of DO in bottom waters compared to the main basin and Cook's Bay. The abundance of difflugiid testate amoebae in ragweed-rich sediments (**Figure 3.10**) records the availability of algae (Riddick et al. 2016), since they are herbivores (McCarthy, 1984), whereas centropyxids can tolerate harsh conditions because bacteria are their primary food supply (Neville et al. 2011).

Similar changes in NPP assemblages characterised the ragweed rise in cores from Cook's Bay and from the main basin of Lake Simcoe (Danesh et al. 2013; Volik et al. 2016). Planktonic/ eutrophic desmids (e.g., *Staurastrum chaetoceras, S. pingue,* and *Cosmarium formosulum*) and eutrophic *Pediastrum* (e.g., *Pediastrum boryanum var boryanum* and *P. boryanum var pseudoglabrum*) are abundant in the upper parts of cores throughout Lake Simcoe (**Figures 3.6** & **3.11**), replacing assemblages dominated by oligotrophic *Pediastrum integrum* and benthic desmids characteristic of meso-oligotrophic conditions (e.g., the genus *Euastrum*).

Differences in the algal palynomorph assemblages in modern (ragweed-rich) sediments of Smith's Bay, Cook's Bay and the main basin are attributed to geographic variations (**Table 3.2**). **Table 3.3** provides a comparison of the algal palynomorph assemblages in 'modern' and pre-European (i.e., before the ragweed rise) sediments from Smith's Bay. In Cook's Bay, high concentrations of nutrients and heavy metals (compared to core SB-2 from Smith's Bay – **Figures 3.4** & **3.7**) and relatively low palynomorph abundances dominated by planktonic taxa are consistent with high influx of material from the East and West Holland Rivers and associated dilution of the algal palynomorphs (Hall & Smol, 1996; Smol, 2010; Haas, 2010; Mudie et al. 2011). **Table 3.2** shows that *Cucurbitella tricuspis* is abundant in the upper part of the ragweed zone in Cook's Bay and the main basin, but this indicator of nutrient loading and low DO (Roe et al. 2010; Neville et al. 2011; Patterson et al. 2012; Danesh et al. 2013; Drljepan et al. 2014) is almost absent in Smith's Bay (Volik, 2014). The main basin has the highest algal palynomorph abundances (dominated by planktonic taxa), with the exception of desmids, which are most abundant in Smith's Bay, the closest site to the major outflow of the lake and where the highest benthic abundance is also observed.

Table 3.2: Algal palynomorph (of known affinity) and testate amoeba abundance from the surface sediments (upper 10 cm) of Smith's Bay, the main basin and Cook's Bay. As it may be both planktonic and benthic, *Cosmarium formosulum* was not included in these counts and in difflugiid counts, *Cucurbitella tricuspis* was tabulated separately (data from Volik, 2014 and this study).

	Benthic desmid half-cells	Planktonic desmid half-cells	*Pediastrum* coenobia	dinocysts	Centropyxid tests	Holobenthic difflugiid tests	*Cucurbitella tricuspis* tests
Smith's Bay 1cm	52	22	7		8	28	0
2 cm	7	0	1			N/A	
5cm	71	11	8	N/A	8	24	0.2
10 cm	56	20	5		9	24	0.2
Average	**46.5**	**12.3**	**5.25**		**8**	**25**	**0.1**
main basin 2 cm	4	13	24	17	5	45	27
5 cm	1	3	4	3	1	31	20
10 cm	2	1	6	9	1	41	15
Average	**2**	**6**	**11**	**10**	**2**	**39**	**21**
Cook's Bay 1 cm	9	4	22	6	20	8	10
6 cm	11	1	36	7		N/A	
Average	**10**	**2.5**	**29**	**6.5**	**20**	**8**	**10**
		* x1000/ml				* /ml	

Table 3.3: Algal palynomorph (of known affinity) and testate amoeba abundance from the surface sediments (upper 10 cm) and below the ragweed rise (40-50 cm) of Smith's Bay (data from Volik, 2014 and this study). In sediments prior to the ragweed rise, there are fewer desmids, only 3% of which are planktonic (23% in modern sediments. Additionally, *Pediastrum* abundance is lower and centropyxids dominate the testate amoebae assemblage,

	Benthic desmid half-cells	Planktonic desmid half-cells	*Pediastrum* coenobia	Centropyxid tests	Holobenthic difflugiid tests	*Cucurbitella tricuspis* tests
Smith's Bay 1cm	52	22	7	8	28	0
2 cm	7	0	1		N/A	
5cm	71	11	8	8	24	0.2
10 cm	56	20	5	9	24	0.2
Average	**60**	**18**	**7**	**8**	**25**	**0.1**
Smith's Bay 40 cm	43	0	6	22	11	0
45 cm	35	1	3	25	8	0
50 cm	28	1	2	29	5	0
Average	**35**	**1**	**4**	**25**	**8**	**0**
		* x1000/ml			* /ml	

The presence of mostly eutrophic/ planktonic taxa in the upper section of the main basin and Cook's Bay (e.g., most *Staurastrum, Pediastrum Botryococcus* spp. and dinoflagellate cysts) and the increased prevalence of eutrophic/ planktonic desmids and *Pediastrum* in Smith's Bay, indicate some level of bottom water anoxia from increased BOD (Danesh et al. 2013; Volik et al. 2016). Furthermore, with more turbid water, light penetration decreases. The lack of light for benthic primary producers, combined with low oxygen levels impacts, the benthic ecosystem. These problems extend beyond environmental impact, as cold-water fish that are important to the regional economy are also affected by low DO levels (Winter et al. 2007; Palmer et al. 2011). In Smith's Bay, higher concentrations of benthic algae (e.g., *Cosmarium protractum, C. botrytis, Euastrum bidentatum* and *E. denticulatum*), the absence of planktonic/ eutrophic *Codonella cratera* and near-absence of *Cucurbitella tricuspis* suggests that DO remains fairly high compared with Cook's Bay and the main basin of Lake Simcoe. This, combined with the lower nutrient and metal concentrations found from core SB-2 (compared to Cook's Bay; e.g., zinc = <40 mg/kg vs. ~70 mg/kg and TP = <500 mg/kg vs. ~1000 mg/kg – **Figures 3.4** & **3.7**), indicates that this site in the northern part of the lake, is the least impacted and is less eutrophic.

Rodé (2009) identified perturbation in chironomid assemblages in a core from the main basin in 2007 that were dated around 1830 using the ^{210}Pb age model of Hawryschyn (2010) (**Figure 3.1**). The rarity of diatoms in sediments deposited prior to 1860 precluded the identification of the earliest European settlement, but chlorophyll *a* was present throughout the core, increasing sharply in the latter half of the nineteenth century (Hawryschyn 2010) (**Figure 3.12**). The algal palynomorph data from core LS07 PC5, collected from a depth of 21 m (Volik et al. 2016), were plotted using the age model of Hawryshyn (2010) in **Figure 3.12** and it is clear that green algae and dinoflagellates contribute strongly to the primary productivity, whereas there is little correlation with the diatom record (**Figure 3.12**). The close correlation between concentrations of algal palynomorphs and chlorophyll *a* in the sediment suggests that the ^{210}Pb-constrained age model of Hawryshyn (2010) can be applied to core LS07 PC5, making allowance for the slightly slower rate of sediment accumulation at the deeper 2007 core site (~33 m). This

is important because no reliable radiometric age control is available for core LS07 PC5 (or SB-1/2 and CB-1).

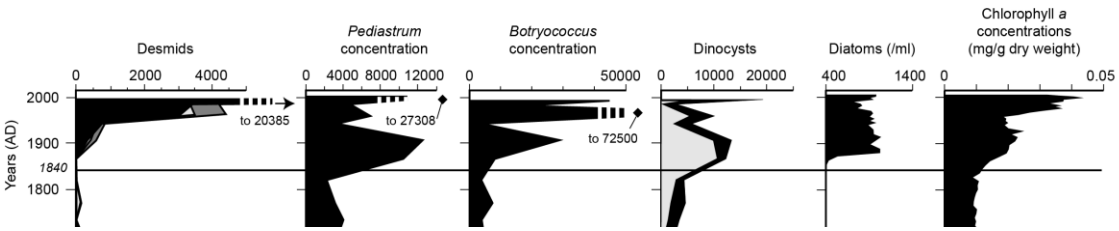

Figure 3.12: Algal palynomorph assemblage from the main basin core LS07 PC5, compared to diatoms and chlorophyll *a* concentrations from core LSMB from the main basin (collected in 2007; Rodé, 2009). An age model was created by Hawryshyn (2010) for this second core, with ^{210}Pb dating for the upper section (~40 cm). Black lines identify historic anthropogenic impact events (ragweed rise, canal construction, eutrophication of Lake Simcoe). There is close correlation between chlorophyll *a* concentrations in core LSMB and LS07 PC5 algal palynomorph record at the same core depths, supporting the use of this age model for LS07 PC5. Minor differences are attributed to a slightly slower rate of sedimentation in the deeper water 2007 core. Conversely, there is little correlation between chlorophyll a concentrations and diatom abundance (chlorophyll *a* data from Hawryshyn, 2010; algal palynomorph data from Volik et al. 2016).

The decline in algal palynomorph abundance around the ragweed rise in core SB-1 and increases in nutrient and metal concentrations from similar core depths from core SB-2 are attributed to siltation due to land clearing by early European settlers. The associated turbidity impedes photosynthesis, particularly impacting benthic algae (i.e., most desmids). Accelerated erosion and siltation associated with land disturbance is also evident in the increase in nutrients (notably nitrate) and lead, zinc, and arsenic beginning just below the ragweed rise. The initial land disturbance is attributed to the establishment of York County by Governor John Graves Simcoe in the 1790s and the construction of Yonge Street/Highway 11 from Toronto to Lake Simcoe along the Iroquois trails connecting Lake Huron to Lake Ontario (LSRCA, 2000). Ekdahl et al. (2007) similarly attributed the decline in benthic diatoms associated with elevated concentrations of heavy metals and nutrients in Crawford Lake (**Chapter 2** & **4**). Varve ages supplemented by several AMS dates allowed them to associate the turbidity with two intervals of agriculture and settlement, first by Iroquoian people, then by Euro-Canadians (Ekdahl et al. 2004). Although their diagrams identify the base of the Euro-Canadian (i.e., ragweed zone at 1867, year of Canadian Confederation), radiocarbon ages on five pine needles and twigs from 25.65 to 26.83 cm in core CL1-F01 are more consistent with an age of 1840 - 1860 (Ekdahl et al. 2004; Geological Society of America, n.d.).

The decline in desmid concentrations (**Figure 3.8**) and slight increase in the eutrophic *Pediastrum boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum* (**Figure 3.9**) from 65 to 55 cm in core SB-1 is similar to the NPP/ geochemical response at the ragweed rise and is therefore believed to be associated with pre-European land disturbance activities. Additionally, in SB-2, and centered at 60 cm, there are slight increases in nutrient and metal concentrations (e.g., nitrate, chromium, copper and zinc – **Figure 3.7**), which may also be attributed to the same pre-European land disturbance activities. **Chapter 2** (Riddick et al. 2016) tentatively associated this with the Wendat/ Huron and from the main basin, an association which will be explored further in **Chapter 4**. Volik et al. (2016) also observed a pre-European anthropogenic impact event, which they attributed to 'Native' settlement (tentatively Wendat). This event is similar to observations from Smith's Bay, in that algal palynomorph abundances are low, however in the main basin the presence of dinoflagellate cysts, *Cucurbitella tricuspis*, and difflugiids dominant testate amoeba assemblage differ (all of which are associated with human impact – **Figure 3.6**).

3.6 Conclusions

Algal palynomorphs show a clear response to widespread Euro-Canadian land clearing and agriculture in the lower Great Lakes region during the mid-nineteenth century. In cores from three sites in western Lake Simcoe, a shift in algal palynomorph assemblages from oligo-mesotrophic to meso-eutrophic records cultural eutrophication in the lower part of the ragweed zone. Although chlorophyll *a* measurements revealed high primary productivity during the nineteenth century, diatoms are rare. Desmids were particularly useful proxies because benthic taxa (most *Cosmarium* spp. and *Euastrum* spp.) were negatively impacted by low light penetration resulting from turbidity and phytoplankton blooms.

Although the response of algal palynomorphs to cultural eutrophication appears to have lagged behind that of testate amoebae, they appear to discriminate between the impact of urbanization in the upper part of the ragweed zone and the earlier land-clearing and agriculture along the western shore of Lake Simcoe. Sediments characterized by high concentrations of heavy metals in both Smith's Bay and Cook's Bay are rich in

palynomorphs of meso-eutrophic planktonic algae, whereas testate amoeba assemblages show little change within the ragweed zone. Algal palynomorph assemblages similar to those associated with early Euro-Canadian land clearing and agriculture were found in sediments with slightly elevated heavy metal and nutrient concentrations well below the ragweed rise in Smiths' Bay. As in lakes from Awenda Provincial Park and Crawford Lake, this evidence of earlier impact has been tentatively attributed to the Wendat (Huron) who had agricultural settlements in Wendake (Huronia) that extended to the northwestern shores of Lake Simcoe by the first half of the seventeenth century.

Variations in algal palynomorph and testate amoeba assemblages in modern sediments at the three sites in western Lake Simcoe are attributed to geographic variations. The main basin core LS07 PC5 was collected from much deeper water, compared to the other two sites; the much lower abundances of benthic algae reflect this. Higher concentrations of both benthic and planktonic desmids and the abundance of benthic difflugiid testate amoebae (and near-absence of the pseudo-planktonic *Cucurbitella tricuspis*) reflects the lower level of impact evident in the elemental analysis of sediments from this site compared with Cook's Bay.

Algal and other non-pollen palynomorphs are common in slides prepared for pollen analysis (particularly in preparations that avoid harsh bases and oxidants, like acetolysis) even in sediments where mineralized microfossils (e.g. diatoms) are not preserved. Their sensitivity to different types of land disturbance and water quality makes them ideal proxies of human impact on watersheds.

3.7 Sources

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Chapter 4: Palynological Record of Pre-European Anthropogenic Impact on Lake Simcoe

Intended for the Journal *Geoarchaeology*

4.1 Introduction

Southern Ontario has a long history of human occupation, with early Paleo-Indian peoples believed to have arrived around 11.5 thousand YBP (years before present) (Jackson et al. 2000). At Rice Lake (**Figure 4.1**), paleolimnological work that included testate amoeba analysis indicated a wetland environment exploited for resources around 10.5 thousand YBP (Sonnenburg et al. 2011, 2012). Archaeological evidence from fish weirs in the Atherley Narrows (Mnjikaning Fish Weirs National Historic Site – east of Smith's Bay, Lake Simcoe), that links Lake Couchiching with Lake Simcoe, suggests that people have inhabited the shores of Lake Simcoe for at least 5,000 years (Parks Canada, 2009). One of the most notable Native groups to have lived around Lake Simcoe is the "Wendat" (or Huron, as the French explorers and missionaries called these Iroquoian people) who, by the time of French discovery, in the early seventeenth century, had migrated to live in Wendake (Huronia) between Lake Simcoe and Georgian Bay (**Figure 4.1**) (Visual Heritage Project, 2012).

The Wendat are an Iroquoian group, consisting of four tribes (**Table 4.1**; **Figure 4.2**). They were Iroquoian agriculturalists and lived in villages with up to 5,000 people. "Iroquoian" is a grouping of tribes with similar language and culture. Another Iroquoian group is the Haudenosaunee, enemies of the Wendat, typically referred to as the Iroquois (Dickason & Newbigging, 2010; Sioui & Labelle, 2014). Wendat settlement in Ontario may have been tied to an alliance with the Algonquin, which was over 250 years old by 1650 CE. Algonquin is another language group and includes tribes such as the Nipissing, Ottawea, Ojibway and Algonkin. The Algonquin who were hunter/ gatherers and lived in small villages (100-500 people) were spread across a vast territory (**Figure 4.1**) (Sioui & Labelle, 2014).

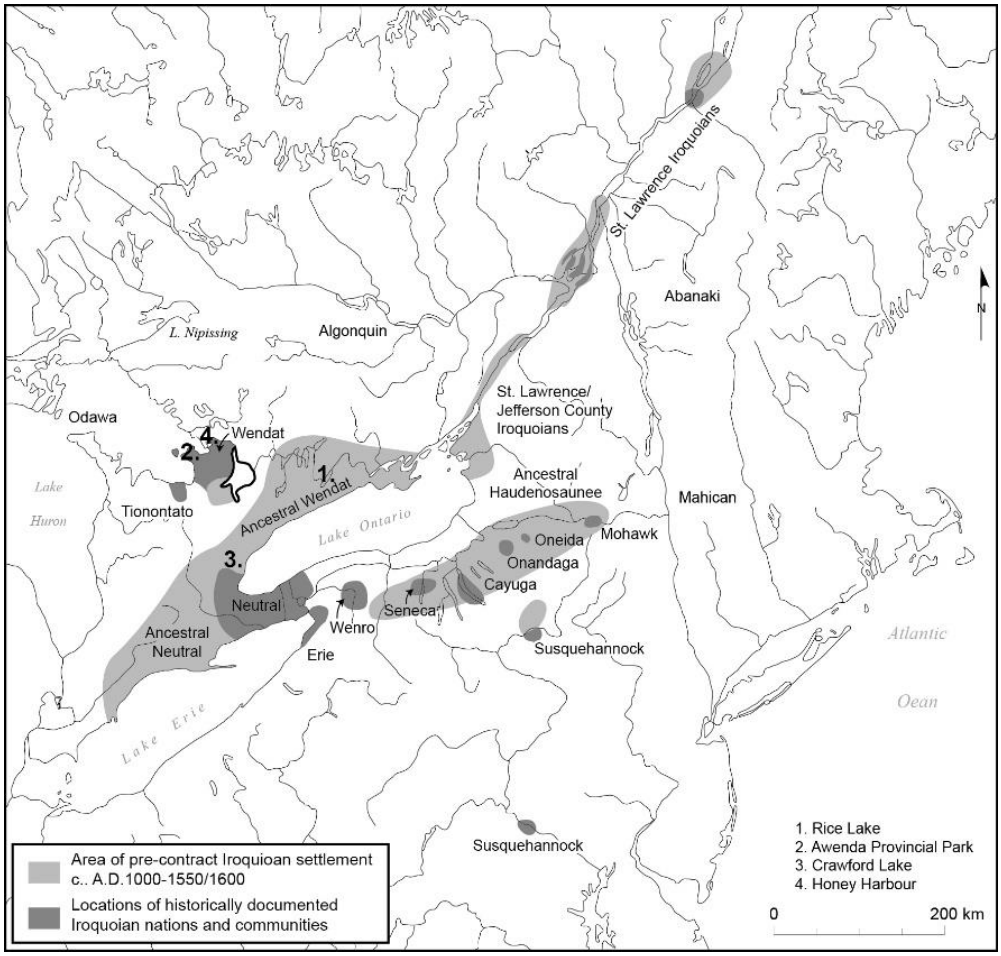

Figure 4.1: Pre-contact and documented Iroquoian territories, with locations of previous geoarcheological studies, including: 1) Rice Lake and three areas with paleolimnological evidence of Wendat settlement: 2) Awenda Provincial Park, 3) Crawford Lake and 4) Honey Harbour. Wendake (Huronia) is identified by the dark grey area labeled Wendat between the northwestern shore of Lake Simcoe (bold outline) and the southeastern shore of Georgian Bay/ Lake Huron (modified from Birch & Williamson, 2015).

Table 4.1: The Wendat Confederacy (Trigger, 1987; Birch & Williamson, 2015)

Tribe	Territory	Wendat Confederacy
Attignawantan (Bear)	Resided in Wendake (possible since the 1300s)	Founding Member of the Confederacy in the mid-15thC.
Attigneenongnahac (Cord)	Resided in Wendake (possible since the 1300s)	Founding Member of the Confederacy in the mid-15thC.
Arendarhonon (Rock)	Move to Wendake ~1590 from Trent Valley	Likely Joined around 1590
Tahontaenrat (Deer)	Move to Wendake ~1610 from Lake Ontario	Likely Joined around 1610

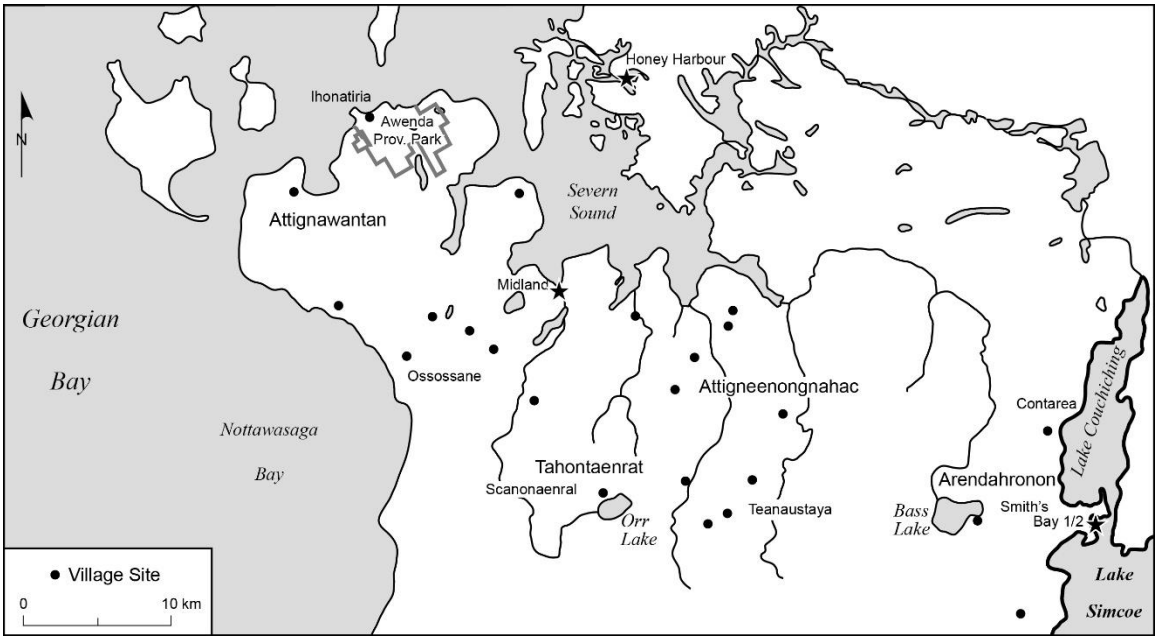

Figure 4.2: Distribution of Wendat (Huron) villages and tribes in the early seventeenth century (modified from Warrick, 2008)

The Wendat first arrived in Ontario around the eleventh century and permanently settled by the thirteenth century. Their initial territories included the north shore of Lake Ontario, the Trent River valley and the area between Lake Simcoe and Georgian Bay, the latter traditionally referred to as Wendake (**Figure 4.1**) (Sioui & Labelle, 2014; Birch & Williamson, 2015). In the early to mid-1600s the Wendat, who by then had formed a confederacy, were entirely concentrated in Wendake (Trigger, 1987; Sioui & Labelle, 2014). According to the Demographic Theory (Sioui, 1999), the Wendat-Algonquin alliance was strategic, allowing for the trade of Wendat agricultural goods and game caught by the Algonquin (Dickason & Newbigging, 2010; Sioui & Labelle, 2014). This alliance may have brought forth territorial and geopolitical security and Sioui and Labelle (2014) emphasize the closeness of this relationship, pointing out that the Algonquin-Wendat borders overlapped and they sometimes lived amongst each other. Hunter (1909) notes that Algonquin villages existed in north and south Orillia before the Jesuit missions were established. **Table 4.1** provides information on the Wendat tribes, approximate date of entry into the confederacy, and pre-confederacy territory.

The Wendat became allies of the French, developing a trade relationship and even allowing Jesuit missionaries to set up missions within their borders, like the one in

Midland, the site of the Sainte-Marie Among the Hurons shrine (Dickason & Newbigging, 2010). Between 1633 and 1639, not long after the migration of the Tahontaenrat (Deer) tribe, epidemics reduced the population of Wendake by as much as 60% (Warrick, 2003). In 1650 the Haudenosaunee massacred and dispersed the remaining Wendat population, the survivors settling outside of Quebec City and in Michigan, while others were incorporated into the Haudenosaunee (both as willing participants and as captives) (Birch & Williamson, 2015). After the Wendat were dispersed, the Ojibway moved into the area (Hunter, 1909; Ringer, 2008).

4.1.1 Paleolimnological Evidence of the Wendat in Southern Ontario

Paleolimnological analysis has identified a pre-European anthropogenic impact event attributed to the Wendat at several sites in southern Ontario. The best-known of these is Crawford Lake (**Figure 4.1**), which has been the subject of many studies (e.g., Ekdahl et al. 2004, 2007; Turton & McAndrews, 2006; McAndrews & Turton, 2010; McCarthy & Krueger, 2013; Krueger & McCarthy, 2016) following the initial discovery of evidence of an Iroquoian (thought to be early Wendat) village. The village was reconstructed following archeological excavations between 1973 and 1987 and is managed by Conservation Halton (Finlayson, 1998; Conservation Halton, 2016). In addition to this small, seasonally occupied, village (~200 people) located 150 m from the lake, there were seven other (known) villages within 3 km of the lake, ranging from 200-3000 people. All of these villages date between 1200 and 1500 CE (Dodd et al. 1990; Finlayson 1998).

Crawford Lake is a meromictic lake which exhibits exceptional preservation of many groups of microfossils (e.g., rotifer loricae, diatoms and dinoflagellate cysts) that record increased siltation and nutrient influx to the lake, associated with Native as well as Euro-Canadian settlement (**Figure 4.3**). In the Iroquoian zone, dinoflagellate cyst, rotifer and planktonic diatom abundances increase (benthics decrease) and assemblages do not fully recover in the intermediate time between ca. 1500 and the early nineteenth century. Additionally, the virtual absence of bioturbation produces annually-laminated sediments (varves), which allow for very high resolution when comparing results with archeological and historical records. Non-arboreal pollen (e.g., grasses), increased pollen of cultivars (e.g., sunflower & corn) and spores of their pathogens (e.g, corn smut) are present in

sediments deposited between 1268 and 1486 CE and some of these (e.g., corn and corn smut) are also found in European zone (**Figure 4.3**) (Byrne & McAndrews, 1975; Ekdahl et al. 2004 & 2007; Krueger & McCarthy, 2016). Additionally, increases in metals and nutrients are tied to increased erosion from land clearing in both zones (**Figure 4.4**) (Ekdahl et al. 2007).

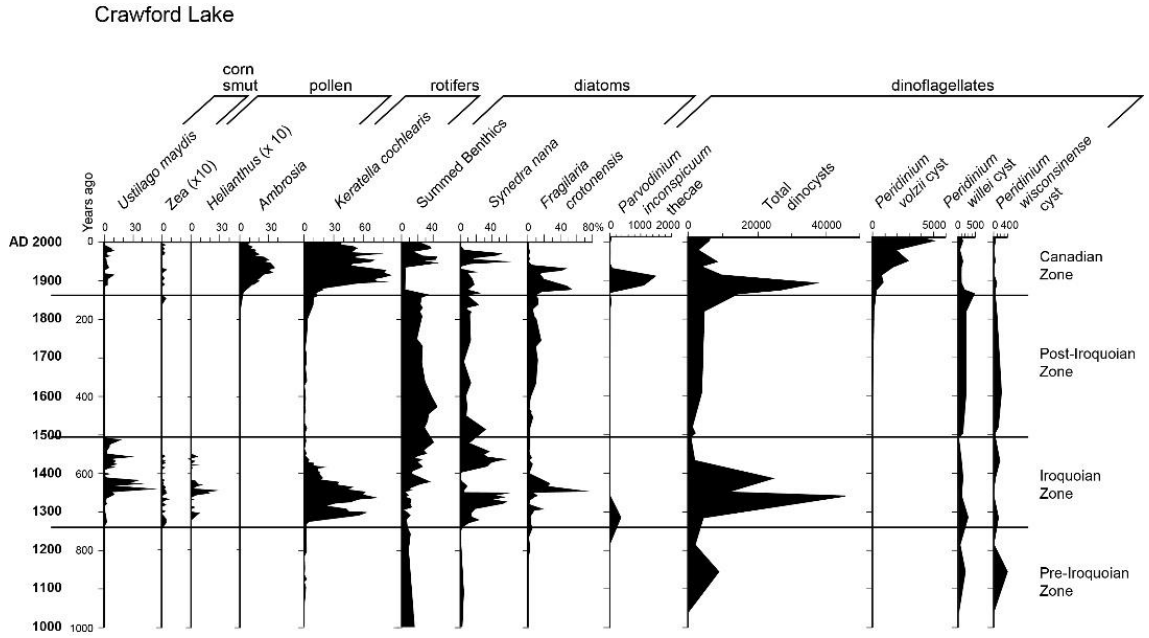

Figure 4.3: Microfossil signature of Euro-Canadian and Iroquoian settlement on the shores of Crawford Lake (modified from Ekdahl et al. 2004, 2007; Turton & McAndrews, 2006; McAndrews & Turton, 2010; Krueger & McCarthy, 2016). Cultivars such as corn and sunflower, and spores of cultivar pathogens like corn smut, are found in both settlement zones. Additionally, in these zones, rotifers, planktonic diatoms and dinoflagellates increase, while benthic diatoms decrease. The Euro-Canadian period differs from the Iroquoian period primarily in the presence of cysts attributed to the dinoflagellate *Peridinium volzii* and the abundance of ragweed pollen (*Ambrosia*). Aquatic ecosystems did not recover in the intermediate time between settlement periods, clearly illustrated in the diatom record. This site has excellent chronological control with both annually laminated sediments (varves) and radiocarbon dating. While this figure positions the base of the Canadian zone in the latter half of the nineteenth century, radiocarbon dates (from core CL1-F01) indicate that the base of the Canadian zone is more consistent with ages between 1840 – 1860 (Ekdahl et al. 2004; Geological Society of America, ftp://rock.geosociety.org/pub/reposit/2004/2004129.pdf).

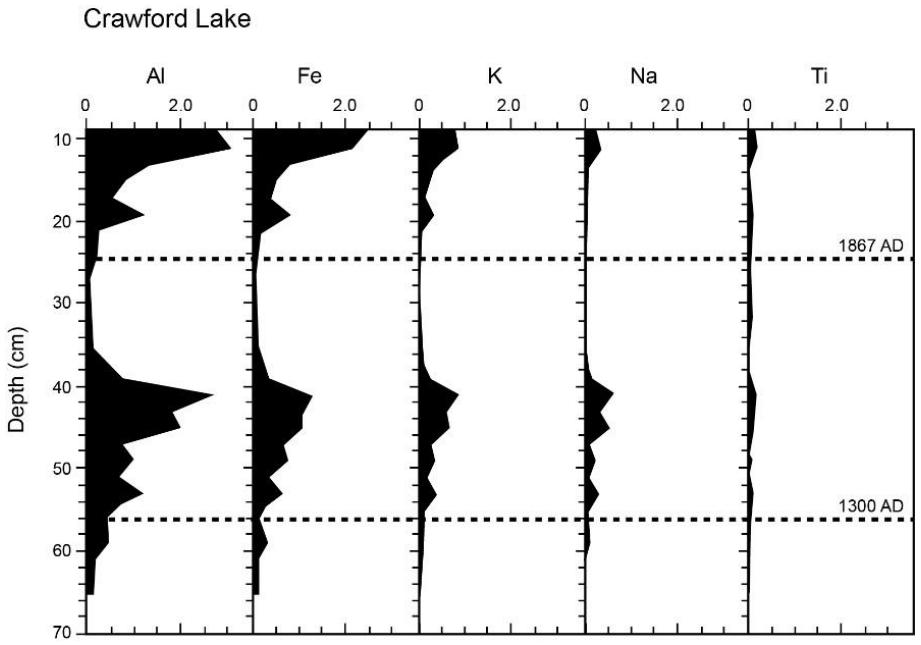

Figure 4.4: Geochemical signature of Euro-Canadian and Iroquoian settlement on the shores of Crawford Lake (Ekdahl et al. 2007). Each of the metals and nutrients (aluminum (Al), iron (Fe), potassium (K), sodium (Na) and titanium (Ti)) increase in association with settlement events. Between the two settlement periods, concentrations of these elements drop to pre-disturbance levels.

Burden et al. (1986a) collected cores from two lakes (Second and Gignac lakes) in and around what is now Awenda Provincial Park (**Figure 4.1**) on the Penetanguishene Peninsula. This area was subject to 10,000 years of human history and Wendat agriculture from the mid-fifteenth to mid-seventeenth centuries, followed by regrowth of forests after the defeat of the Wendat by the Iroquois. This peninsula was the heart of Wendake, housing 13-14 Attignawantan (Bear) villages, this tribe comprising as much as half the Wendat population (Ste. Marie Among the Hurons, n.d.; Warrick, 2008). Three villages existed within 1 km of Second Lake, while one village was known to have existed on the western end of Lake Gignac. During the Wendat period, there was a change in the arboreal pollen assemblage, reflective of forest succession, where beech, maple and hemlock abundances decrease (i.e., old growth) and oak, birch and pine abundances increase (**Figure 4.5**). There were increases in non-arboreal pollen and spores (e.g., grasses and bracken ferns) possibly attributed to growth in abandoned fields (**Figure 4.5**). Burden et al. (1986a) also found corn pollen in the Iroquoian zone; however note that, while this is an excellent indicator of Native faming, it is uncommon. The rarity of cultivar pollen (primarily insect pollinated) was also noted by Turton & McAndrews, 2006 (see **Figure 4.3**, where corn and sunflower pollen curves are

exaggerated 10X to increase their visibility). Prior to Wendat zone in Second Lake, the algal palynomorph assemblage was dominated by *Peridinium wisconsinense*, which decreases in the Wendat zone as *Pediastrum* increases (**Figure 4.5**). In Gignac Lake, *Pediastrum* and *Peridinium willei* increase in the Wendat Zone, while *P. wisconsinense* decrease (Burden et al. 1986a). The eutrophication evident in the algal assemblage is likely caused by farming-induced soil erosion that transported elements like sodium, magnesium, barium, aluminum, and titanium into the lake (Burden et al. 1986b).

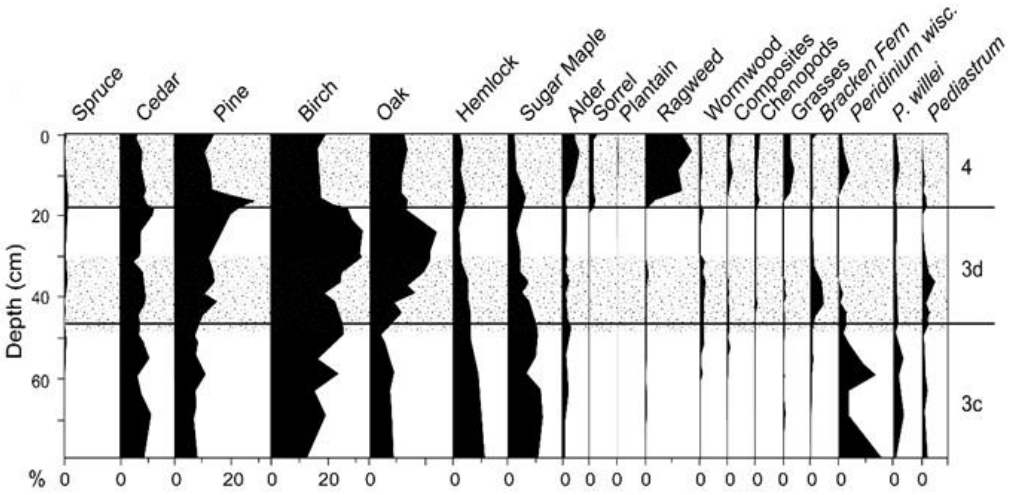

Figure 4.5: Microfossil signature of Euro-Canadian (stippled zone 4) and Iroquoian settlement (stippled area in zone 3d) from Second Lake (modified from Burden et al. 1986a). Early-European settlement is identified by the increase in ragweed pollen, which was dated to the mid-1800s in nearby Wye Marsh, Midland (Chittenden, 1990). Iroquoian settlement can be identified by increase in non-arboreal pollen and spores, particularly bracken fern. The changes in the pollen record are comparatively subtle for the Iroquoian period, however algal palynomorphs respond in a more analogous way. Cysts of *Peridinium wisconsinense* abundances fall sharply in response to Iroquoian settlement while *Pediastrum* abundances increase.

McCarthy et al. (2011) attributed increases in dinoflagellate cyst in sediments from Honey Harbour (across Severn Sound from the Penetang Peninsula) (**Figure 4.1**) to Wendat and European occupation, respectively. Additionally, and in line with findings by Burden et al. (1986a), both the putative Wendat and Euro-Canadian zones (confirmed by ^{210}Pb chronology) were dominated by cysts of *Peridinium willei* (whose identity was determined through culturing and rDNA analysis), whereas sediments deposited prior to and between the mid-seventeenth and mid-nineteenth centuries were dominated by cysts produced by *Peridinium wisconsinense* (**Figure 4.6**).

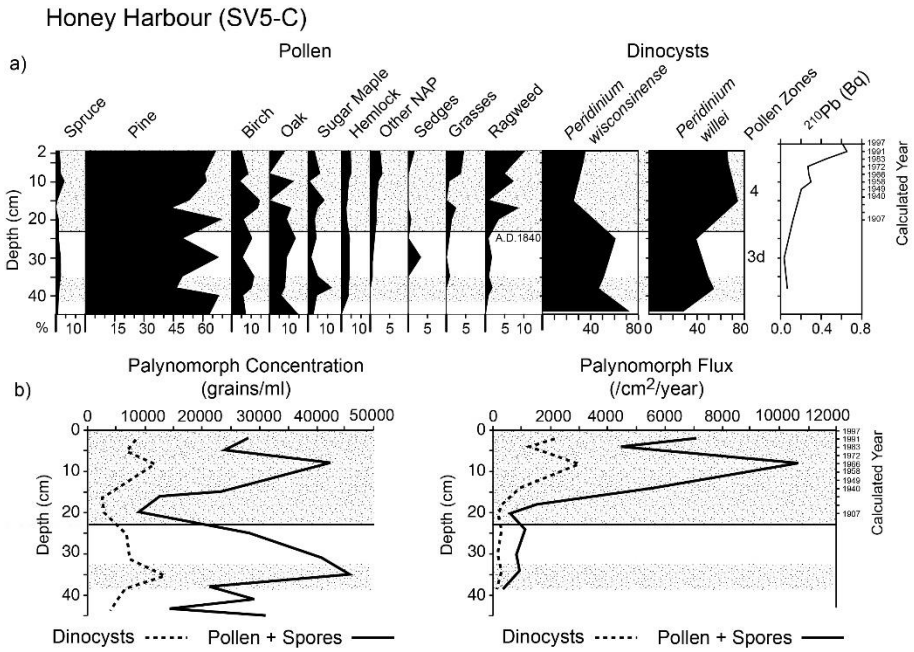

Figure 4.6: Microfossil signature of Euro-Canadian (stippled zone 4) and Iroquoian settlement (stippled area in zone 3d) from Honey Harbour (modified from McCarthy et al. 2011). Euro-Canadian in zone 4 is identified by the increase in ragweed pollen. Similar to findings from Awenda Provincial Park, where the pollen record responds subtly to Iroquoian settlement (in the lower part of zone 3d), algal palynomorphs respond in line with Burden et al. (1986a) where *Peridinium wisconsinense* abundances fall and *P. willei* becomes dominant.

4.1.2 Palynological Evidence of Anthropogenic Impact on Lake Simcoe

Lake Simcoe (**Figure 4.1**), the largest lake in Ontario (other than the Laurentian Great Lakes), has been the subject of several micropaleontological studies of anthropogenic impact in recent years (e.g., Rode, 2009; Hawryshyn, 2010; Hawryshyn at al. 2012; Danesh et al. 2013; McCarthy & Krueger, 2013; Volik, 2014; Riddick et al. 2016a; Volik et al. 2016). Early-European land settlement in this area is characterized by an increase in the abundance of non-arboreal pollen, primarily ragweed pollen. This "ragweed rise" is associated with the large-scale land clearing practiced by European settlers and dated around 1840 CE in Wye Marsh, adjacent to the site of Sainte-Marie Among the Hurons in Midland (Chittenden, 1990). This date is consistent with historic accounts of rapid population growth in the nearby towns of Newmarket and Aurora, between 1841 and 1871 CE (from ~600 to ~3,350 people) and the completion of the first stage of the Ontario, Simcoe and Huron Union Railroad, in 1853 CE (LSRCA, 2000; Railway Pages, 2014).

Earlier impact, just prior to the ragweed rise, is evident in core SB-1 from Smith's Bay, where there is notably a decline in desmids (**Figure 4.7** & **Chapter 3**). This decline is likely the result of erosion and siltation associated with the construction of Yonge Street (Highway 11) when York County was established, beginning in 1790 (LSRCA, 2000). Increased siltation and turbidity associated with intensive land clearing in the Lake Simcoe watershed during the nineteenth and twentieth centuries inhibited photosynthesis; this is evident in the record of benthic algae (i.e., most desmids) in sediments above the ragweed rise in cores from Cook's Bay (Danesh et al. 2013; Volik, 2014), Smith's Bay (Volik, 2014; Riddick et al. 2016, **Chapter 2**) and the main basin of Lake Simcoe (Volik, 2014; Volik et al. 2016; **Chapter 3**). Planktonic algae (e.g., dinoflagellates, *Botryococcus* spp., *Pediastrum* spp. and most species of the desmid genus *Staurastrum*) subsequently increased in abundance in response to cultural eutrophication, but benthic taxa (i.e., most species of *Cosmarium* and *Euastrum*) were negatively impacted by increased biochemical/ biological oxygen demand (BOD) that resulted in bottom water anoxia in Cook's Bay and in the main basin of Lake Simcoe (Danesh et al. 2013; Volik et al. 2016; **Chapter 3**). Herbivorous protozoans (difflugiid testate amoebae, and tintinnid ciliates) also increased in abundance, responding to the increase in their food supply, although low dissolved oxygen (DO) in most parts of Lake Simcoe inhibited benthic protozoans. Planktonic ciliates and the testate amoebae *Cucurbitella tricuspis* were common in the ragweed zone of cores CB-1 and LS07 PC5; unlike most testate amoebae, *C. tricuspis* has a planktonic stage associated with mats of floating Spirogyra (Medioli et al. 1987), which explains its abundance in eutrophic lakes (Roe et al. 2010).

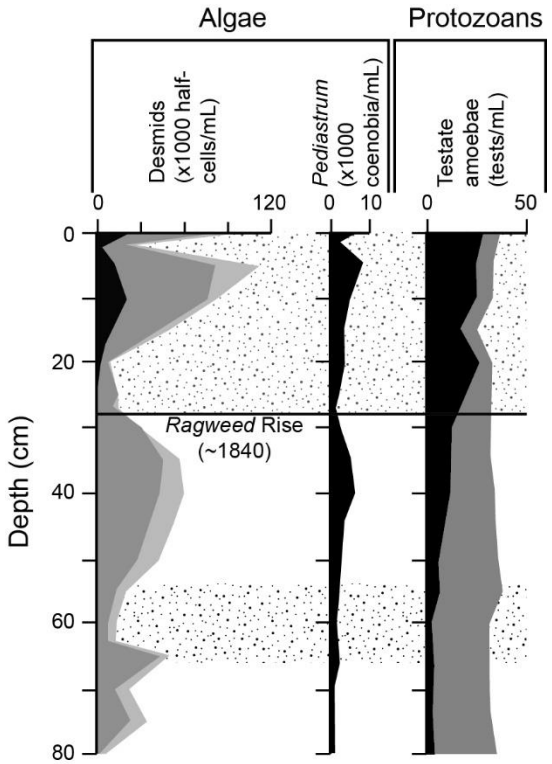

Figure 4.7: Algal palynomorphs (desmids & *Pediastrum*) and testate amoebae from core SB-1 in Smith's Bay (modified from Riddick et al. 2016a; **Chapter 3**). Here, planktonic desmids are in black, benthics are dark grey and desmids of unknown affinity are in light grey. There is a decrease in the abundance of desmids beginning at 35 cm and extending past the ragweed rise between 27 and 25 cm to 20 cm that is attributed to turbidity associated with siltation. The ragweed rise is a regional pollen marker, dated to ca. 1840 (Chittenden, 1990; McAndrews, 1994). The beginning of this desmid decline, prior to the ragweed rise, is attributed to the construction of Yonge Street (Highway 11) when York County was established (ca. 1790). An early, analogous decrease in desmid abundance is observed between 55 and 65 cm, and is attributed to pre-European anthropogenic impact. These decreases in primarily benthic desmid abundance are attributed to turbidity/siltation, whereas planktonic *Pediastrum* were not greatly affected. The sharp increase in herbivorous difflugiid testate amoebae (black) at the expense of bacteria-eating centropyxid (dark grey) taxa, at the time of the ragweed rise records eutrophication.

An increase in nutrients and heavy metals was also measured in sediments rich in ragweed in cores from Cook's Bay and Smith's Bay (**Figure 4.8**). There is also evidence of increased siltation ca. 30 cm below the ragweed rise in Smith's Bay, highlighting a pre-European event prior to the nineteenth century which also caused an increase in heavy metals in core SB-2 and a sharp decline in desmid abundance around the same depth in core SB-1 (Riddick et al. 2016a). Volik et al. (2016) also found evidence of eutrophication and siltation in both the non-pollen palynomorph and testate amoeba assemblages below the ragweed rise in core LS07 PC5 from the main basin of Lake Simcoe.

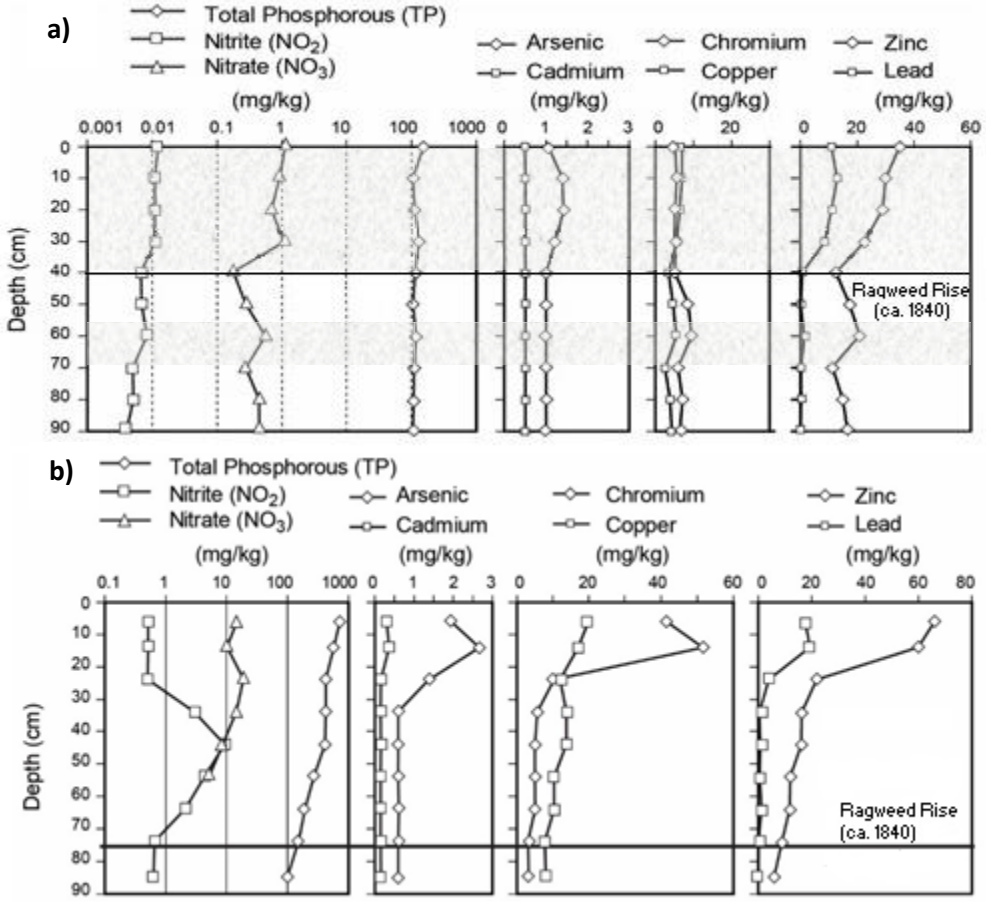

Figure 4.8: Metal and nutrient concentrations from **a)** Smith's Bay (core SB-2) and **b)** Cook's Bay (modified from Danesh et al. 2013 and Riddick et al. 2016a). In Smith's Bay there is an increase in various parameters associated with widespread Euro-Canadian settlement, identified by the ragweed rise, a regional pollen marker (McAndrews, 1994). Additionally, below the ragweed rise (centered at 60 cm) there is another increase in metal and nutrient concentrations, associated with siltation prior to the nineteenth century (pre-European Impact). Human impact zones in Smith's Bay are identified by the stippled areas. In Cook's Bay, several phases of Euro-Canadian development were identified (Danesh et al. 2011) but the record in this core does not extend far back enough to observe any possible pre-European impact event.

Both of these pre-European disturbances were tentatively attributed to the Wendat who had villages along the northwestern shore of Lake Simcoe (Riddick et al. 2016a, 2016b; Volik et al. 2016), but natural events (e.g., forest fires) could have produced increased erosion, resulting in greater influx of sediments and limiting nutrients to Lake Simcoe. This chapter investigates the pre-European impact event, examining proxies of anthropogenic land clearing and agriculture (pollen and spores associated with cultivars, micro-charcoal) in core sediments from Smith's Bay. Additionally, the algal palynomorph and geochemical signature will be compared as they relate to land disturbance from Euro-Canadian colonization of the region and land disturbance

observed below the ragweed rise, in cores from Smith's Bay and the main basin of Lake Simcoe.

4.2 Methods

4.2.1 Coring

Core SB-1 is an 80 cm-long sediment core collected using a Rowley Dahl sampler from Smith's Bay in October 2012 at a water depth of 2.15 m (Volik, 2014). Core SB-2 is a 90 cm-long sediment core (replicate of SB-1), collected using a Rowley Dahl sampler from Smith's Bay in April 2014 at a water depth of ~2 m (Riddick et al. 2016a).

4.2.2 Palynological Processing

Palynological processing and analysis was completed at Brock University, using techniques modified from Faegri & Iversen (1975), avoiding harsh bases (KOH) and oxidation (acetolysis) that damage non-pollen palynomorphs (Riddick et al. 2016a). A tablet containing a known number of *Lycopodium clavatum* spores (marker spore) was added to quantify palynomorph concentrations following Stockmarr (1971). Processing and analytical techniques are described in detail by Volik (2014), Riddick et al. (2016a) and **Chapter 3**.

Acetolysis makes analysis of oxidation-resistant palynomorphs like pollen and fungal spores easier by removing organic debris, particularly amorphous organic matter, that can obscure pollen and spores on slides. It was performed on our samples only after algal palynomorphs were analyzed because desmids were shown to be negatively impacted by this oxidation technique (Riddick et al. 2016a), and it remains unclear what impact oxidation has on other non-pollen palynomorphs. Pollen and fungal spores were analyzed of from acetolysed preparations from cores SB-1 (pollen originally presented in **Chapter 3**) and SB-2, with particular focus on non-arboreal pollen and cultivar pathogens (i.e., corn smut) in order to identify human impact on the vegetation. A minimum of 200 pollen spores were counted in each sample and fungal spores were quantified using *Lycopodium clavatum* spores (50 spores per sample). McArdrews et al. (1973) 'Key to the Quaternary Pollen and Spores of the Great Lakes Region' was used for pollen identifications and McAndrews & Turton (2010) was used for the

identification of corn smut. The ragweed rise, a well-dated datum, also serves to correlate between the replicate cores. Microscopic charcoal (micro-charcoal: small (typically <40 μm) carbonized particles produced by burning vegetation) was analyzed in palynological slides from core SB-2 and quantified using *Lycopodium clavatum* marker spores (50 spores per sample). In addition, the ecology of the desmid assemblages in core SB-1 and the main basin core LS07 PC5 was examined.

4.3 Results

Representative non-arboreal pollen and fungal spore results from core SB-2 have been presented in **Figure 4.9**. Ragweed and grass pollen are present in the samples from 20, 28 & 36 cm, with ragweed ranging from 7 to 12%. Non-arboreal pollen increases again at 57 and 63 cm. This corresponds with corn smut spores, which are found in the samples from 20, 28 & 36 cm and at 63 cm. Micro-charcoal was found in low abundance (between ~600 and ~2,100 pieces/mL) in four intervals (20, 28, 36 & 63 cm). Additionally, sunflower pollen was found at 63 cm (**Figure 4.9**). **Figure 4.10** provides fungal spore results (corn smut) from core SB-1, with non-arboreal pollen modified from **Chapter 3**. The ragweed rise occurs at 26 cm. Corn smut spores make up ~1 - 3% of the fungal palynomorph assemblage in ragweed-rich sediments and ~2% at 60 cm. Sunflower pollen was found at 60 and 63 cm.

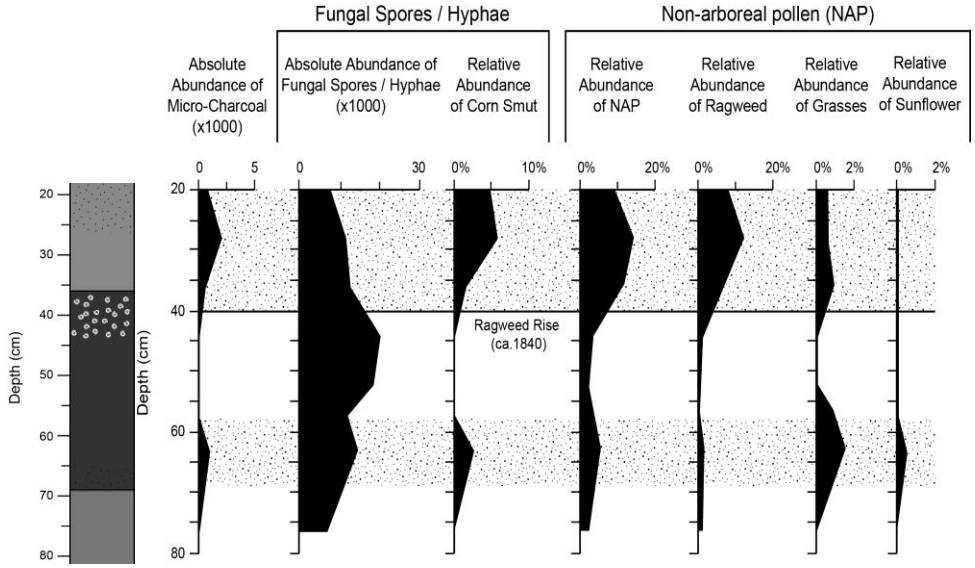

Figure 4.9: Micro-charcoal, non-arboreal pollen (ragweed, grass and sunflower) and fungal spores (including corn smut) from core SB-2. The Euro-Canadian impact zone is identified through an increase in ragweed pollen (7 – 12 %), which is a regional pollen marker (McAndrews, 1994). Additionally in this

zone micro-charcoal abundances increase (max. ~2,100 pieces/mL), non-arboreal pollen increase (9 – 11 %) and corn smut is present (2 – 6%). Below ragweed-rich sediments in a sample at 63 cm, micro-charcoal abundance increases again (~1,000 pieces/mL), corn smut is present (3%), non-arboreal pollen increases (5%) and sunflower (max. 0.5%) are present (pre-European impact zone). Human impact zones are denoted by the stippled areas.

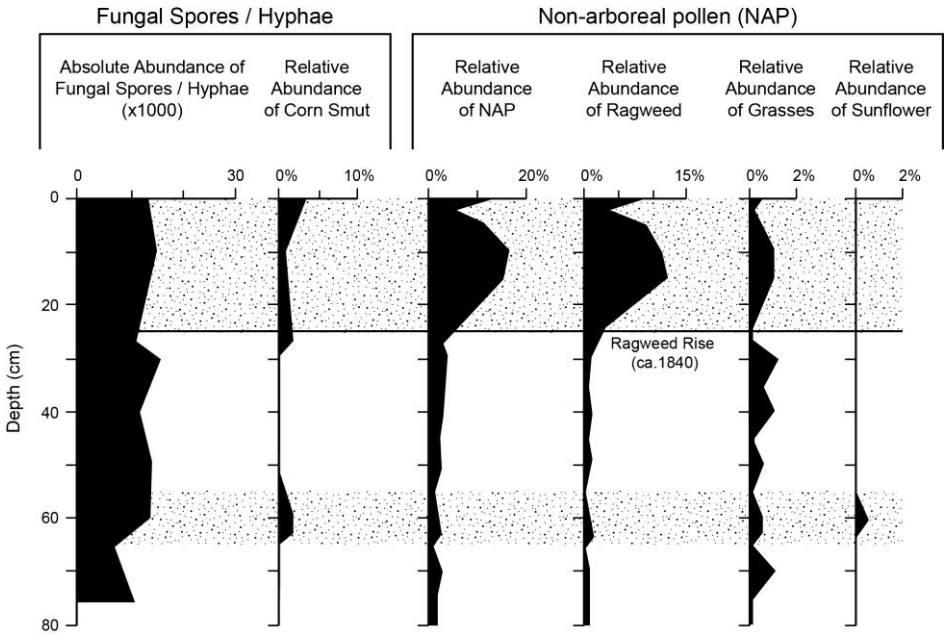

Figure 4.10: Non-arboreal pollen (ragweed, grass and sunflower) (modified from **Chapter 3**) and fungal spores (corn smut) from core SB-1. **Chapter 3** found that while wide spread early-European settlement is denoted by the ragweed rise, a regional pollen marker (McAndrews, 1994), initial activities (e.g., the establishment of York county, construction of Highway 11/ Yonge St.) are observable beginning at 35 cm (i.e., decrease in desmid abundance associated with turbidity/ siltation, see **Figure 4.7**). Additionally and in Euro-Canadian zone corn smut is present (1 – 3%). Below ragweed rise, centered at 60-63 cm corn smut (2%) and sunflower (max. 0.5%) are present (pre-European impact zone). Human impact zones are denoted by the stippled areas.

The desmid assemblage from core SB-1 based on trophic status as described by Šťastný (2010) is presented in **Figure 4.11**. Oligo-mesotrophic taxa dominate until 40 cm, except in the pre-European zone, centered at 60 cm (when oligotrophic taxa all but disappear and oligo-mesotrophic taxa decline in relative abundance). Above 40 cm, eu-mesotrophic taxa dominate and oligo-mesotrophic taxa disappear above 24 cm. Oligotrophic taxa are only present before and between stippled impact zones.

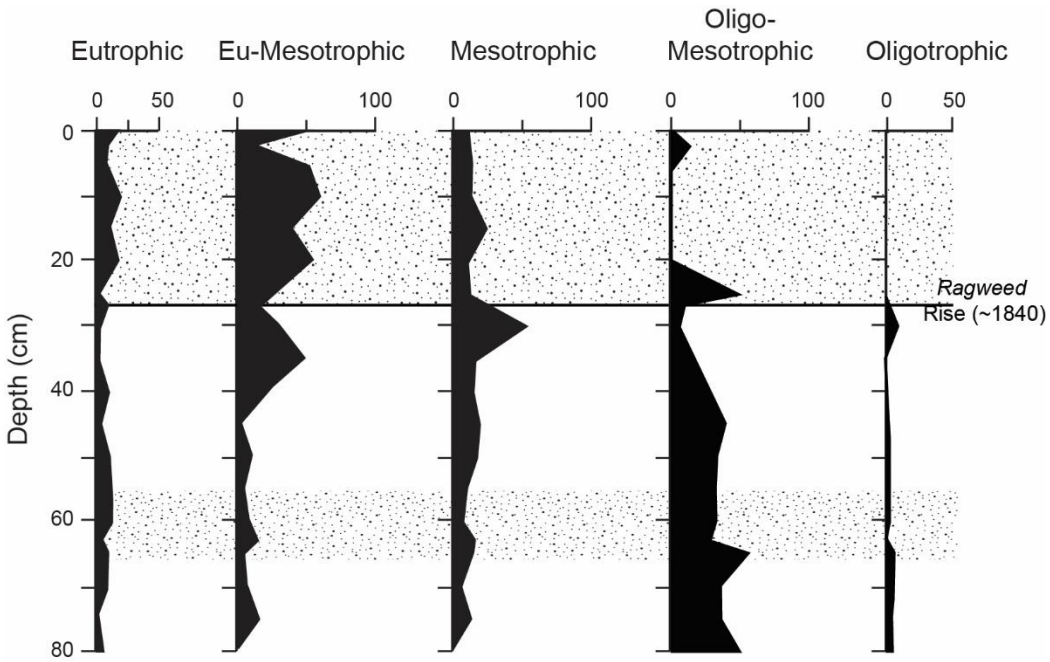

Figure 4.11: Desmid assemblage (% abundance) from core SB-1 (modified from **Chapter 3**), organized by trophic status (following Šťastný, 2010). The desmid assemblage is dominated by eu-mesotrophic taxa in the upper 40 cm. Prior to this, the assemblage is dominated by oligo-mesotrophic taxa, except in a zone centered at 60 cm (pre-European zone). At 40 cm, the decline of oligo-mesotrophic taxa in favour of eu-mesotrophic taxa corresponds to an initial decline in desmid abundance that persists through the ragweed rise to 20 cm (see **Figure 4.7**). While the ragweed rise is a regional pollen marker, dated to ca. 1840 (Chittenden, 1990; McAndrews, 1994), **Chapter 3** attributed the analogous conditions before this (beginning at 35 cm) to the construction of Yonge Street (Highway 11).

The desmid assemblage from core LS07 PC5 based on the trophic status derived from Šťastný (2010) is presented in **Figure 4.12**. Meso-oligotrophic taxa dominate the assemblage just prior to the human impact zone (starting at ~57 cm), identified by Volik at al. (2016). These taxa largely disappear and there is an increase in eutrophic, then mesotrophic taxa, through to the ragweed rise. The uppermost sample is dominated by eutrophic and eu-mesotrophic taxa.

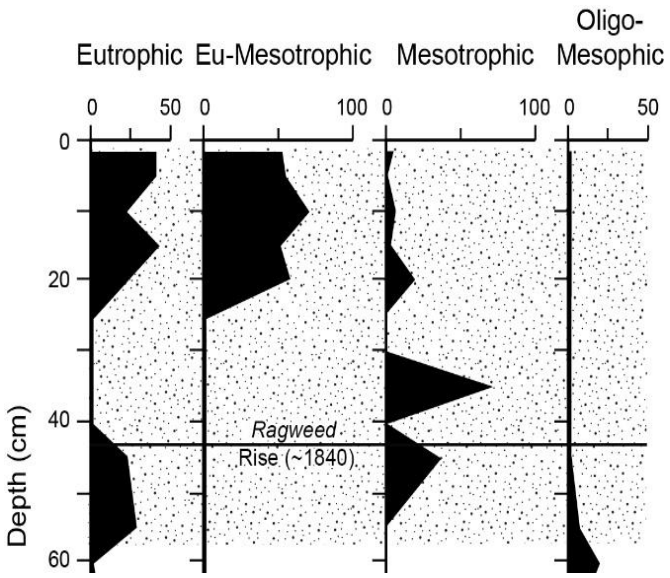

Figure 4.12: Desmid assemblage (% abundance) from core LS07 PC5, organized by trophic status (following Šťastný, 2010). The highest abundance of olio-mesotrophic taxa occurs prior to human impact (stippled area). These decline in favour of eutrophic taxa, with a subsequent peak in mesotrophic taxa just prior to the ragweed rise, attributed to Wendat and/or early-European settlement (low rates of sediment accumulation prior to the ragweed rise do not allow separate phases to be discriminated). Surface sediments are dominated by eutrophic and eu-mesotrophic taxa almost exclusively.

4.4 Discussion

The sharp increase in ragweed and other non-arboreal pollen throughout southern Ontario since the nineteenth century reflects the extensive land-clearing practiced by Euro-Canadian settlers. The pollen signature of Iroquoian/ Wendat (Huron) villages around the middle of the last millennium is subtle. Burden et al. (1986a) note changes in the arboreal pollen and non-arboreal pollen record as an indicator of the Iroquoian zone (e.g., decreases in beech and maple, increases in oak and pine & grasses) in Awenda Provincial Park (**Figure 4.5**), citing Crawford Lake as having a similar response to land clearing followed by forest succession after the villages were abandoned. However, McCarthy et al. (2011) note little in the way of a pollen response to the Wendat. The pollen of cultivars (that tend to be insect-pollinated) is rare, even at sites like Crawford Lake and Awenda Provincial Park that are in very close proximity to several villages occupied over an extensive period. The sites that record land disturbance below the ragweed rise in Lake Simcoe, in contrast, are more distal from Wendat villages, with the Arendarhonon (Rock) tribe having migrated from the Trent Valley only around 1590 CE (**Figure 4.2**) (Warrick, 2008). There is a slight increase in non-arboreal pollen, notably Asteraceae [Compositae], Chenopodiaceae (**Plate 4.1**), and *Artemisia* below the ragweed rise in core

LS07 PC5 from the main basin of Lake Simcoe that Volik et al. (2016) tentatively attributed to Wendat agricultural settlements (**Figure 4.13**). There is little evidence of pre-European agriculture in the pollen record from Smith's Bay core SB-1 other than two grains of sunflower pollen (**Plate 4.1**) which were identified in samples from 60 and 63 cm. Spores of the corn fungal pathogens, corn smut and minor leaf spot were also found between 60 and 63 cm (**Plate 4.1**; **Figure 4.10**). In core SB-2, there is a slight increase in the relative abundance of non-arboreal pollen around 63 cm, where corn smut, minor leaf spot and sunflower pollen were also identified (**Figure 4.9**). Additionally, in core SB-2, micro-charcoal identified in pollen slides was more abundant in samples from 63 cm and in ragweed-rich samples above 34 cm (**Figure 4.9**). Evidence of agriculture and minimal micro-charcoal abundance may indicate fire from Native activities (e.g., slash-and-burn and cooking/ warmth) (Clark & Royall, 1995).

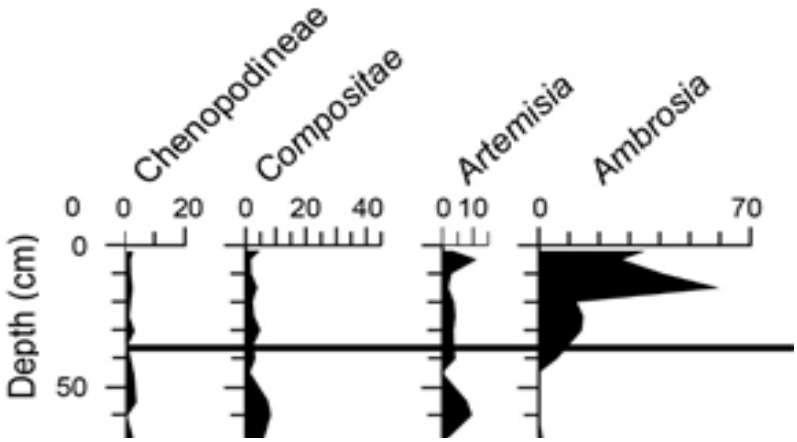

Figure 4.13: Non-Arboreal pollen from core LS07 PC5 (modified from Volik et al. 2016). Increases in Asteraceae [Compositae], Chenopodiaceae, and *Artemisia* are observed, centered around 60 cm, and below the ragweed rise are tentatively associated with Wendat settlement.

Spores produced by fungal pathogens of cultivars in Crawford Lake were found to better represent both Iroquoian and Euro-Canadian agriculture than the pollen of the cultivars themselves (McAndrews & Turton, 2010). The discovery of spores of fungal corn pathogens in both ragweed-rich sediments and around 60 cm in both cores from Smith's Bay supports this observation (**Figures 4.9** & **4.10**).

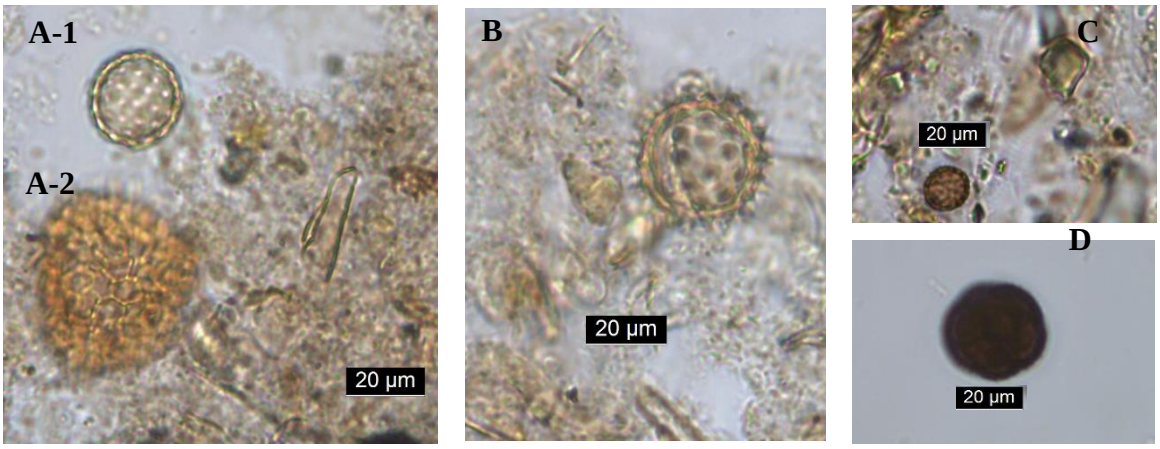

Plate 4.1: Select non-arboreal pollen and corn fungal pathogens from Lake Simcoe core SB-1 – chenopod pollen (A-1); Marker spore (A-2); sunflower pollen (B); corn smut fungal spore (C); minor leaf spot fungal spore (D). Photographs were taken using a Leica MC 120 HD digital imaging camera.

Non-pollen palynomorphs of primary producers (such as the cysts of dinoflagellates and *Pediastrum*) and their consumers (like the remains of rotifers) record cultural eutrophication of lakes near Wendat villages (Burden et al. 1986a; Turton and McAndrews, 2010; McCarthy et al. 2011; McCarthy and Krueger 2013; Krueger and McCarthy, 2016). Preservation of these organic-walled microfossils (palynomorphs) is promoted by the depressed concentrations of dissolved oxygen in bottom water resulting from biochemical oxygen demand, particularly within and just above the organic-rich sediments on the lakebed, as a result of sediment oxygen demand (Krueger and McCarthy 2016). Algal palynomorph assemblages in core SB-1 from Smith's Bay and core LS07 PC5 from the main basin of Lake Simcoe record increased nutrient availability below the ragweed rise, where there is an increase in abundance of mesotrophic & eutrophic desmids at the expense of those who prefer oligotrophic and meso-oligotrophic conditions (**Figures 4.11** & **4.12**). In the main basin, Volik et al. (2016) noted that dinoflagellate cysts appear as a result of human (tentative Wendat) settlement (**Figure 4.14**), which is similar to findings in Crawford Lake (**Figure 4.3**) and Honey Harbour (**Figure 4.5**) where dinoflagellate cyst abundance increases. Additionally, the low abundance of desmids (primarily benthic), together with the appearance of planktonic dinoflagellate cysts and presence of other primarily planktonic algae (e.g., *Pediastrum*) is similar to findings from Crawford Lake, where benthic diatoms decrease in favour of planktonic taxa (**Figure 4.3**). The dominance of planktonic taxa can be seen in Smith's Bay (core SB-1) as well, where benthic desmids decrease around 60 cm (**Figure 4.7**).

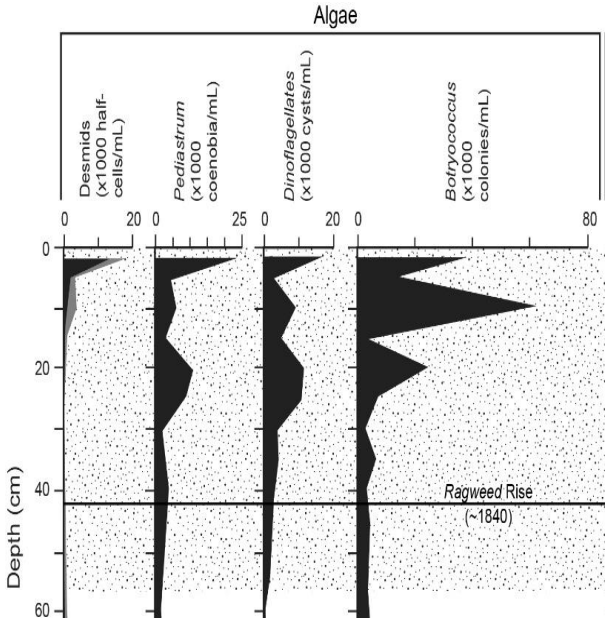

Figure 4.14: Algal palynomorphs from core LS07 PC5 (modified from Volik et al. 2016). Dinoflagellate cysts appear in response to human settlement (stippled area). The abundances of algal palynomorphs remain constant until above the ragweed rise. Abundances of primarily eu-mesotrophic taxa planktonic taxa increase above 30 cm.

The limiting nutrients and elements that promote eutrophication are derived from accelerated erosion ("siltation") associated with land clearing. Higher rates of sedimentation and geochemical changes record greater terrigenous influx around the middle of the last millennium as well as during the nineteenth century in Crawford Lake. Here iron, potassium, sodium and titanium increase, associated with Iroquoian and Euro-Canadian settlement, respectively (Ekdahl et al. 2007) (**Figure 4.5**). This is similar to findings of Burden et al. (1986b), who also attribute increases in geochemical concentrations (e.g., sodium, magnesium, barium, aluminum and titanium) to Wendat and Euro-Canadian settlement. Concentrations of heavy metals (notably zinc, copper and chromium) in sediments around 60 cm as well as in ragweed-rich sediments in core SB-2 record accelerated erosion in the Smith's Bay watershed. Similarly, concentrations of nutrients in the sample from 60 cm, although not high, are close to values in the lower part of the ragweed zone (**Figure 4.8**).

Increased turbidity associated with siltation (and to a lesser extent, in response to higher phytoplankton productivity) inhibited photosynthesis in benthic desmids, both in the ragweed zone and in earlier sediments attributed to Wendat villages. In the main basin of Lake Simcoe Volik et al. (2016) found very low abundances of benthic desmids in

relatively non-arboreal pollen-rich sediments below the ragweed rise, leaving the palynomorph assemblage dominated by planktonic groups (e.g., dinoflagellates and the colonial green algae *Pediastrum* and *Botryococcus*) (**Figures 4.13** & **4.14**). Increased turbidity is also recorded around 60 cm and in the lower part of the ragweed zone in core SB-1 by a decline in the relative abundance of benthic desmids (**Figure 4.7**). Ekdahl et al. (2004, 2007) documented a similar decline in benthic diatom abundance in Crawford Lake during the Iroquoian period, while planktonic diatoms increased in abundance, responding to the increase in nutrient availability, further impeding light penetration (**Figure 4.3**).

In both Smith's Bay and the main basin of Lake Simcoe, conditions in the pre-European (tentative Wendat) impact zone are similar to conditions around the ragweed rise, regionally associated with early-European settlement. In the examples of Crawford Lake (**Figure 4.3**), Awenda Provincial Park (**Figure 4.5**) and Honey Harbour (**Figure 4.6**), the analogous nature of human impact, particularly of agricultural societies (i.e., Wendat and early-European) is evident and important for the identification of pre-European human settlement. In the main basin, the abundances of algal palynomorphs are consistent through to the ragweed rise, covering periods associated with the pre-European and early-European settlement (**Figure 4.14**) (Volik et al. 2016). In Smith's Bay (core SB-1), there is a decrease in desmid abundance (**Figure 4.7**) and presence of cultivars/ cultivar pathogens (cores SB-1 & SB-2), an increased presence of micro-charcoal (cores SB-2) (**Figures 4.9** & **4.10**) and higher geochemical concentrations (**Figure 4.8**), associated with both pre-European and early-European settlement.

4.5 Conclusion

The impact of agricultural peoples can be detected through microfossil and geochemical proxies in lake sediments. In Crawford Lake, Awenda Provincial Park (Second Lake and Lake Gignac) and Honey Harbor, evidence of siltation and cultural eutrophication are attributed to Iroquoian (Wendat/ Huron) and Euro-Canadian settlement and agriculture. There are many similarities in the response of water bodies to both human impact intervals (e.g., decreased benthic algae, increasing planktonic algae and herbivores, increase in meso-eutrophic taxa at the expense of oligo-mesotrophic taxa). The pollen

record shows a much more subtle response to the Iroquoian settlements compared with the rapid increase in ragweed and other non-arboreal pollen in response to the widespread land-clearing practiced by early European settlers.

Micropaleontological proxies of eutrophication and siltation below the ragweed rise in cores from the main basin of Lake Simcoe and Smith's Bay were tentatively attributed to Wendat settlements. This is supported by the presence of palynomorphs produced by cultivars and their pathogens and elevated quantities of micro-charcoal in sediments from Smith's Bay that are similar to those in the lower part of the ragweed zone. Geochemical analysis of the sediments from core SB-2 also revealed heavy metal and nutrient concentrations similar to those associated with early European settlement and agriculture in the Lake Simcoe watershed. Additionally, the algal palynomorph assemblage reflects similar conditions to that of early-European settlement, indicated by the ragweed rise (e.g., low/ decreasing abundance of desmids, shift away from oligo-mesotrophic conditions).

The paleolimnological record of Wendat in Lake Simcoe is relatively subtle compared to that in Crawford Lake and Awenda Provincial Park, reflecting the greater distance of the core sites from population centers. The Arendarhonon (Rock) tribe migrated to the northeastern coast of Lake Simcoe only around 1590 CE (Warrick, 2008), only ~60 years before the displacement of the Wendat from Wendake (Huronia) by the Haudenosaunee. It is plausible that the paleolimnological response, which is analogous to that of early-European settlement, is the result of this migration.

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Chapter 5: Conclusion

Geoarchaeology, the application of geography and earth sciences in archaeology, can include the use of microfossils as proxies of aquatic and terrestrial ecosystems and cultural eutrophication (Pollard, 1999). The application of microfossils in archaeology dates back to the early 1900s, before the advent of radiocarbon dating, when pollen was used as a dating tool. Since then, the application of microfossils has expanded greatly (e.g., studies of agriculture, diet and resource exploitation). The purpose of this investigation was to use the palynological record as a proxy of human impact on Lake Simcoe, specifically examining evidence of impact prior to Euro-Canadian colonization. The increase in *Ambrosia*/ragweed pollen (ragweed rise), which is a regional pollen marker of land clearing, dated to ca. 1840 CE (Chittenden, 1990; McAndrews, 1994; Ekdahl, 2004) provides chronological control in these marly sediments where radiocarbon dates have proven unreliable (Volik et al. 2016).

Non-pollen palynomorphs are the acid-resistant remains of algae, protozoans, invertebrate animals, plants, and fungi in samples prepared for pollen analysis. Most palynologists process lacustrine sediments using acetolysis, an oxidising technique developed in the mid-twentieth century to remove "unwanted" organic debris from pollen slides. Unacetolysed preparations from Lake Simcoe were rich in desmid half-cells, and these ecologically diverse charophyte algae proved useful as proxies of land disturbance and eutrophication. The same residues were re-examined following acetolysis and far fewer half-cells were found, and assemblages were dominated by relatively robust half-cells of *Cosmarium* (Riddick et al. 2016, **Chapter 2**). The susceptibility of desmids to oxidation probably explains their absence from the geoarcheological literature despite their utility as proxies of anthropogenic impact, and palynologists are urged not to acetolyse lacustrine samples.

Analysis of the geographic variations in microfossil distribution on the Lake Simcoe lakebed indicates that Smith's Bay is less impacted site than Cook's Bay or the main basin and is consistent with lower concentrations of nutrients and heavy metals/ metalloids in cores from Smith's Bay than Cook's Bay (**Figures 3.4** & **3.7**). Cook's Bay

and the main basin of Lake Simcoe have higher abundances of eu-mesotrophic/ planktonic taxa (**Figures 3.6** & **3.11**), whereas the algal palynomorph assemblage in Smith's Bay remains desmid-dominated (most of which are benthic) (**Table 3.2**). Lakebed sediments from the main basin and Cooks's Bay are rich in dinoflagellate cysts, *Botryococcus* colonies, loricae of the planktonic tintinnid ciliate *Codonella cratera* and the pseudo-planktonic testate amoeba *Cucurbitella tricuspis*, all associated with more eutrophic waters and oxygen-depleted bottom waters (Danesh et al. 2013; Volik et al. 2016).

As fungi are common pathogens, fungal palynomorphs have been used in geoarcheological studies to identify agriculture, and spores of fungal corn pathogens (e.g., corn smut/ *Ustilago maydis*) were identified within ragweed-rich sediments as well as around 60 cm in both cores from Smith's Bay, Lake Simcoe (SB-1 & SB-2) (**Figures 4.9** & **4.10**). This provides evidence of land disturbance and eutrophication well below the ragweed rise to be attributed to Wendat (Huron) who were agriculturalists. As at other Wendat sites, human settlement and agriculture is much more evident in the NPP than in the pollen record (Burden et al. 1986; Turton & McAndrews, 2006; McAndrews & Turton, 2010; McCarthy et al. 2011; McCarthy and Krueger, 2013; Krueger &McCarthy, 2016).

In Smith's Bay, the palynological record identified several phases of human impact, as described below:

European Settlement

Slightly elevated levels of ragweed and other non-arboreal pollen that immediately precede the sharp ragweed rises are accompanied by a decline in algal palynomorphs, and the near-absence of desmids in core SB-1 (**Figure 4.7**). This is attributed to increased turbidity/siltation resulting from land clearing and erosion, and is attributed to the establishment of York County and construction of Yonge Street (Highway 11) by Governor Simcoe's troops in the 1790s (LSRCA, 2000).

Elevated concentrations of lead, zinc and arsenic as well as nitrates in the upper 35 cm of core SB-2 (**Figure 3.7**) are associated with the ragweed rise. This regional pollen marker, identified at 26 cm in core SB-1 has been dated to ca. 1840 CE (Chittenden, 1990; McAndrews, 1994; Ekdahl et al. 2004), is consistent with population growth in the Lake Simcoe catchment and the completion of the first stage of the Ontario, Simcoe and Huron Union Railroad, in 1853 CE (LSRCA, 2000; Railway Pages, 2014). Lower concentrations of benthic desmids abundance above the ragweed rise records high turbidity and an increase in eutrophic/eu-mesotrophic algae and in herbivorous difflugiid testate amoebae (**Figure 4.7**) records increased nutrient influx attributed to primarily agricultural settlements from the mid- nineteenth to mid-twentieth century.

The increase in eu-mesotrophic/planktonic desmids and *Pediastrum* (**Figure 3.8**) records cultural eutrophication resulting from the post-WWII population increase and industrialization. The resulting increase biochemical/biological oxygen demand and sedimentary oxygen demand produced low dissolved oxygen concentrations that have been a concern, as cold-water fish (e.g., lake trout and whitefish) are an important part of the region's economy(Winter et al. 2007; Palmer et al. 2011).

Wendat Settlement

There is evidence of turbidity and eutrophication in the algal palynomorph record well below the ragweed rise in Smith's Bay. Around 60 cm in core SB-1 there is a sharp decrease in desmid abundance, notably the usually dominant meso-oligotrophic *Cosmarium pyramidatum*/ *C. pseudopyramidatum* together with a decline in the meso-oligotrophic *Pediastrum simplex* var. simplex and the oligotrophic *Pediastrum integrum* (**Figure 4.7**). Concentrations of zinc and nitrates are almost as high as they are just above the ragweed rise and concentrations of copper and chromium are higher than anywhere else in the core around 60 cm in core SB-2 (**Figure 4.8**). The impact of Lake Simcoe appears analogous to that associated with early-European agricultural settlement immediately above the ragweed rise. Analysis of fungal spores/hyphae and re-analysis of non-arboreal pollen from core SB-1 revealed the presence of spores of *Ustilago maydis* (corn smut) and *Epococcim nigrum* (Minor Leaf Spot), fungal cultivar pathogens, and *Helianthus* (sunflower), a native cultivar, in this pre-European zone (**Figure 4.10**).

Concentrations of corn smut spores at 63 cm in core SB-2 were also as high as in the lower part of the ragweed zone, as were concentrations of micro-charcoal. Minor leaf spot and sunflower were also present at 63 cm (**Figure 4.9**). This pre-European event has been attributed to Native agricultural settlements, as in similar paleolimnological studies from Crawford Lake (Ekdahl et al. 2004, 2007; Turton & McAndrews, 2006; McAndrews & Turton, 2010; Krueger &McCarthy, 2016), Awenda Provincial Park (Burden et al. 1986) and Honey Harbour (McCarthy et al. 2011). The pre-European paleolimnological response observed in Smith's Bay is thought to be the result of the migration of the Wendat/ Huron Arendarhonon (Rock) tribe to Wendake/Huronia around 1590 CE. They inhabited the northeastern coast of Lake Simcoe until 1650, when the Wendat were displaced from Wendake by the Haudenosaunee (**Figure 4.2**) (Warrick, 2008). This supports the tentative association of a pre-European paleolimnological response with the Wendat by Volik et al. (2016).

5.1 Future Research

Lake Simcoe is relatively removed from significant Wendat population centers, as was Honey Harbour, however using non-pollen palynomorphs, settlement zones were still established as the organisms who generate these microfossil respond to cultural eutrophication in aquatic ecosystems. As such, it is then possible to assess the impact of pre-historic peoples on the environment and perhaps identify areas of archaeological interest, employing methodology found in this document. Sonnenburg et al. (2013) demonstrated that detailed testate amoebae analysis may be used to the same end. While non-pollen palynomorphs were instrumental in this thesis, other proxies (e.g., geochemical, testate amoebae and pollen) provided key information, highlighting the importance of a multi-proxy approach. Adding methodologies found here with those of Sonnenburg et al. (2013) may yield more robust studies for North American geoarchaeology in the future.

Desmids have been shown to be sensitive to land clearing and associated runoff and siltation; this results in turbidity (evident in a sharp decrease in the abundance of benthic desmids as reduced light penetration inhibits photosynthesis) and increased influx of metals and nutrients (evident in an increase of eutrophic/ eu-mesotrophic taxa at the

expense of oligotrophic/ oligo-mesotrophic taxa). This was seen in the record of Smith's Bay associated with Wendat agriculture (confirmed by the presence of sunflower pollen and the spores corn smut and minor leaf spot) and with Euro-Canadian agriculture beginning with the establishment of Simcoe County in 1790 CE. There is little/ no evidence of human impact on Lake Simcoe between the dispersal of the Wendat by the Haudenosaunee, even though there are historic accounts that the Ojibwa moved into the territory abandoned by the Wendat; the hunter-gatherer lifestyle of these people did not impede the reforestation that succeeded the abandoned fields. While the widespread land clearing associated with Euro-Canadian settlement and agriculture allowed ragweed and other herbs to proliferate producing the regional "ragweed rise", it is noteworthy that even the relatively modest alteration to the mixed forest in the Lake Simcoe watershed resulting from Wendat agriculture between ca. 1590 – 1650 CE is discernible in the desmid record of Smith's Bay.

Desmids also allow the largely agricultural settlements in the Lake Simcoe watershed to be differentiated from the increasingly urban/ suburban settlements and increasing industrial activity through the 20th century, particularly following the Second World War. This impact was primarily a decline in water quality associated with effluent from industrial and municipal water treatment plants and runoff from roads and settlement of airborne particulates. The major environmental problem in Lake Simcoe, the decline in bottom water oxygen associated with biochemical oxygen demand due to eutrophication, is recorded by a decline in benthic desmids and the proliferation of planktonic desmids that prefer eutrophic or eu-mesotrophic conditions.

The methods and analytical techniques employed in this thesis are of use to other archeological projects. While the microfossil groups will change in different settings, the idea remains the same. In the coastal marine setting of the Burgaz Harbor project, benthic foraminiferal, diatom and ostracod taxa would be negatively impacted by land clearing and associated turbidity, while various types of planktonic algae would increase in response to nutrient influx.

The Burgaz archaeological site is located on the Datça Peninsula in the Muğla Province, Turkey. This site is thought to be the original home of the Knidians (Old Knidos), prior to their movement to Tekir or New Knidos, at the western tip of the peninsula. The primary occupation period for Burgaz is thought to be from the Geometric Period to the Hellenistic Period (~900 - 300 BCE), but it is likely that the site is occupied in some form after this time (Tuna et al. 2005).

A team from Middle East Technical University (METU), directed by Numan Tuna began excavating the settlement in 1993. In collaboration with the METU team, Elizabeth Greene (Brock University) and Justin Leidwanger (Stanford University) initiated the Burgaz Harbors Project in 2011, to focus on the coastal and harbour features of the site (INA, 2015; Tuna et al. 2005). The site's long trajectory of maritime interaction is marked by four harbours, identified by general chronological use as Harbors 1-4. In –the team collected two cores from outside Harbor 1, the installation closest to the urban core; a third core was collected from within the harbor. These sediments are being processed for foraminifera, grain size and Loss on Ignition (LOI) analysis. Ideally pollen and non-pollen palynomorph analysis can also be completed. Additional coring is planned for the future. Analysis of new cores may be subject to pollen, ostracod, foraminifera, heavy metal and nutrient analysis.

Microfossils have been used in conjunction with studies of ancient harbour sites before. For example, Marriner et al. (2005) were interested in the placement and size of an ancient harbor in Tyre, Lebanon and how it relates to the existing harbor. Using litho- and biostratigraphical data (including foraminiferal and ostracod assemblages) derived from sediment cores, they were able to determine that the ancient harbor existed in the same place as the modern, though it was about twice the size. They were also able to determine the later period of harbor use, where economic decline in the area, after the Byzantines, resulted in infilling with sediments form the Medieval period onward (sediments from Roman and Byzantine periods having been dredged up in harbor maintenance practices). Foraminifera, such as *Amphistegina* spp. and *Peneroplis planatus* are abundant during the period of harbor use; indicating shallow water and a sheltered, calm marine environment. Corresponding Ostracod analysis yield similar results with

taxa such as, *Loxoconcha sp*. and *Xestoleberis sp.*, indicating a marine-lagoon environment and *Loxoconcha elliptica*, indicating a sheltered harbour connected to the sea.

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Appendix A: Smith's Bay Microfossil Data

SB-1 Arboreal Pollen Raw Data															
Depth (cm)	***Pinus***	***Picea***	***Tsuga***	***Abies***	***Betula***	***Acer***	***Ulmus***	***Fraxinus***	***Quercus***	***Tillia***	***Nyssa***	***Carya***	***Alnus***	***Fagus***	**Total AP**
0	70	4	6	2	16	1	1	1	2	1	0	0	1	1	106
5	80	2	1	0	18	1	1	0	2	1	0	0	0	1	107
10	84	3	1	5	11	3	2	2	3	1	0	1	1	2	119
15	77	2	4	0	17	1	1	1	1	0	0	0	0	0	104
20	66	0	7	6	13	1	1	0	1	1	0	1	2	1	100
25	91	5	3	1	8	4	0	1	3	3	0	0	0	1	120
30	57	1	5	0	45	7	5	2	5	5	0	1	0	6	139
35	70	3	14	2	41	6	2	4	7	3	0	0	0	4	156
40	83	4	6	2	28	13	3	2	9	4	1	0	0	4	159
45	53	1	3	1	41	7	4	6	4	7	1	0	1	1	130
50	65	4	8	0	57	12	6	2	4	11	1	1	2	11	184
55	63	1	2	0	45	12	19	1	6	11	1	1	3	10	175
60	39	1	2	0	59	11	17	1	8	13	1	2	1	16	171
65	52	1	1	3	31	7	7	2	7	8	0	1	3	13	136
70	84	1	4	5	42	5	7	7	6	21	0	0	0	13	195
75	38	0	3	1	33	4	6	5	4	11	0	1	2	12	120
80	79	0	9	2	4	4	6	2	3	1	1	1	1	25	138

Analyst: Olena Volik (Volik, 2014)
Lycopodium Tablet: 10,850 +/-200 spores
Volume: 5 m

Absolute Abundance (%A) & % Error (E): SB-1 Arboreal Pollen

Depth	*Pinus*		*Picea*		*Tsuga*		*Abies*		*Betula*		*Acer*		*Ulmus*		*Fraxinus*		*Quercus*		*Tillia*		*Nyssa*		*Carya*		*Alnus*		*Fagus*	
(cm)	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E
0	0.66	0.09	0.04	0.04	0.06	0.04	0.02	0.03	0.15	0.07	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.03	0.01	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.02
5	0.75	0.08	0.02	0.03	0.01	0.02	0.00	0.00	0.17	0.07	0.01	0.02	0.01	0.02	0.00	0.00	0.02	0.03	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
10	0.71	0.08	0.03	0.03	0.01	0.02	0.04	0.04	0.09	0.05	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.01	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.02
15	0.74	0.08	0.02	0.03	0.04	0.04	0.00	0.00	0.16	0.07	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.66	0.09	0.00	0.00	0.07	0.05	0.06	0.05	0.13	0.07	0.01	0.02	0.01	0.02	0.00	0.00	0.01	0.02	0.01	0.02	0.00	0.00	0.01	0.02	0.02	0.03	0.01	0.02
25	0.76	0.08	0.04	0.04	0.03	0.03	0.01	0.02	0.07	0.04	0.03	0.03	0.00	0.00	0.01	0.02	0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
30	0.41	0.08	0.01	0.01	0.04	0.03	0.00	0.00	0.32	0.08	0.05	0.04	0.04	0.03	0.01	0.02	0.04	0.03	0.04	0.03	0.00	0.00	0.01	0.01	0.00	0.00	0.04	0.03
35	0.45	0.08	0.02	0.02	0.09	0.04	0.01	0.02	0.26	0.07	0.04	0.03	0.01	0.02	0.03	0.02	0.04	0.03	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.02
40	0.52	0.08	0.03	0.02	0.04	0.03	0.01	0.02	0.18	0.06	0.08	0.04	0.02	0.02	0.01	0.02	0.06	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.03	0.02
45	0.41	0.08	0.01	0.02	0.02	0.03	0.01	0.02	0.32	0.08	0.05	0.04	0.03	0.03	0.05	0.04	0.03	0.03	0.05	0.04	0.01	0.02	0.00	0.00	0.01	0.02	0.01	0.02
50	0.35	0.07	0.02	0.02	0.04	0.03	0.00	0.00	0.31	0.07	0.07	0.04	0.03	0.03	0.01	0.01	0.02	0.02	0.06	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.06	0.03
55	0.36	0.07	0.01	0.01	0.01	0.02	0.00	0.00	0.26	0.06	0.07	0.04	0.11	0.05	0.01	0.01	0.03	0.03	0.06	0.04	0.01	0.01	0.01	0.01	0.02	0.02	0.06	0.03
60	0.23	0.06	0.01	0.01	0.01	0.02	0.00	0.00	0.35	0.07	0.06	0.04	0.10	0.04	0.01	0.01	0.05	0.03	0.08	0.04	0.01	0.01	0.01	0.02	0.01	0.01	0.09	0.04
65	0.38	0.08	0.01	0.01	0.01	0.01	0.02	0.02	0.23	0.07	0.05	0.04	0.05	0.04	0.01	0.02	0.05	0.04	0.06	0.04	0.00	0.00	0.01	0.01	0.02	0.02	0.10	0.05
70	0.43	0.07	0.01	0.01	0.02	0.02	0.03	0.02	0.22	0.06	0.03	0.02	0.04	0.03	0.04	0.03	0.03	0.02	0.11	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.04
75	0.32	0.08	0.00	0.00	0.03	0.03	0.01	0.02	0.28	0.08	0.03	0.03	0.05	0.04	0.04	0.04	0.03	0.03	0.09	0.05	0.00	0.00	0.01	0.02	0.02	0.02	0.10	0.05
80	0.57	0.08	0.00	0.00	0.07	0.04	0.01	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.18	0.06

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

SB-1 Non-Arboreal Pollen Raw Data													
Depth (cm)	**AP**	***Artemisia***	***Ambrosia***	**Poaceae**	**Chenopodiaceae**	***Iva***	**Compositae**	***Typha***	**Cyperaceae**	***Chara***	***Myriophyllum***	***Heilianthus***	**Total**
0	174.5	1	20	1	0	0	0	3	3	0	0	0	202.5
5	178	0	18	1	1	0	0	1	2	0	0	0	201
10	176.5	1	23	2	3	0	1	4	0	0	0	0	210.5
15	176	3	25	2	0	0	0	0	1	0	0	0	207
25	202.5	2	5	0	0	0	0	0	3	0	0	0	212.5
27*	275.5	0	3	0	0	0	0	0	0	0	0	0	278.5
30	247.5	2	2	3	0	0	0	0	2	0	0	0	256.5
35	198.5	0	1	1	0	0	0	1	1	0	1	0	203.5
40	206	0	2	2	0	1	1	0	0	0	0	0	212
45	198	1	1	0	0	0	0	1	1	0	0	0	202
50	202.5	0	2	1	0	1	0	1	0	0	0	0	207.5
55	219	1	0	0	0	0	0	0	1	0	0	0	221
60	205.5	0	1	1	0	1	0	0	0	0	0	1	209.5
63*	374	2	1	1	0	0	0	1	2	0	0	1	382
65	215	0	0	0	0	0	0	0	1	0	0	0	216
70	202.5	0	1	2	0	0	0	0	2	0	0	0	207.5
75	197	2	1	0	0	0	0	0	0	0	0	0	200
80	241	2	1	0	0	0	0	0	0	0	0	0	244

Analyst: Nicholas Riddick in 2015/ 2016
Lycopodium Tablet: 10,850 +/-200 spores, 20,848 +/-500 spores for 27 & 63 cm
Volume: 5 mL, 2.5 mL for 27 & 63 cm

Notes: Acetolysed SB-1 sample residues. *27 & 63 cm analyzed without acetolysis

Absolute Abundance (%A) & % Error (E): SB-1 Non-Arboreal Pollen

Depth	*Artemisia*		*Ambrosia*		Poaceae		Chenopodiaceae		*Iva*		Compositae		*Typha*		*Cyperaceae*		*Chara*		*Myriophyllum*		*Heilianthus*	
(cm)	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E
0	0.00	0.01	0.10	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.09	0.04	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.01	0.11	0.04	0.01	0.01	0.01	0.02	0.00	0.00	0.00	0.01	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.01	0.02	0.12	0.04	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
25	0.01	0.01	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
40	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
55	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
63	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01
65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
70	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
75	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

SB-2 Non-Arboreal Pollen & Micro-Charcoal Raw Data													
Depth (cm)	**AP**	***Ambrosia***	**Poaceae**	***Typha***	***Iva***	**Cyperaceae**	***Artemisia***	**Chenopodiaceae**	***Heilianthus***	**Total**		**Lycopodium**	**Micro-Charcaol**
20	188	15	1	2	0	0	0	1	0	207		50	8
28	177.5	24	1	0	0	1	0	2	0	205.5		50	21
36	204	15	2	6	0	2	0	0	0	229		50	6
44	208.5	1	0	2	0	1	2	0	0	214.5		50	0
52	230	1	0	2	0	0	1	1	0	235		50	0
57	216.5	0	2	4	1	1	0	0	0	208.5		50	0
63	191	2	3	3	0	2	0	0	1	202		50	10
76	233.5	2	0	1	0	1	0	0	0	237.5		50	0

Analyst: Nicholas Riddick in 2016
Lycopodium Tablet: 12,500 +/-200 spores
Volume: 2.5 mL

Notes: Acetolysed SB-2 sample residues.

Absolute Abundance (%A) & % Error (E): SB-2 Non-Arboreal Pollen

Depth	*Ambrosia*		Poaceae		*Typha*		*Iva*		Cyperaceae		*Artemisia*		Chenopodiaceae		*Heilianthus*	
(cm)	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E
20	0.07	0.04	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
28	0.12	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00
36	0.07	0.03	0.01	0.01	0.03	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
44	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00
52	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00
57	0.00	0.00	0.01	0.01	0.02	0.02	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
63	0.01	0.01	0.01	0.02	0.01	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01
76	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

SB-1 Fungal Spores Raw Data					
Depth (cm)	**Lycopodium**	**Total Spores**	***Ustilago maydis***	***Sphacelotheca reliana***	***Epicoccum nigrum***
0	50	312	10	1	0
10	50	346	3	2	3
27*	50	66	1	0	0
30	50	371	0	0	0
40	50	272	0	0	0
50	50	330	0	0	0
60	50	306	5	0	0
63*	50	64	1	0	3
65	50	162	0	0	0
75	50	240	0	0	0

Analyst: Nicholas Riddick in 2016
Lycopodium Tablet: 10,850 +/-200 spores, 20,848 +/-500 spores for 27 & 63 cm
Volume: 5 mL, 2.5 mL for 27 & 63 cm

Notes: Acetolysed SB-1 sample residues. *27 & 63 cm analyzed without acetolysis

SB-2 Fungal Spores Raw Data					
Depth (cm)	**Lycopodium**	**Total Spores**	***Ustilago maydis***	***Sphacelotheca reliana***	***Epicoccum nigrum***
20	50	80	4	1	0
28	50	115	7	1	0
36	50	130	2	0	0
44	57	233	0	0	0
52	50	184	0	0	0
57	50	120	0	0	0
63	50	145	4	0	1
76	50	70	0	0	0

Analyst: Nicholas Riddick in 2016
Lycopodium Tablet: 12,500 +/-200 spores
Volume: 2.5 mL

Notes: Acetolysed SB-2 sample residues.

Absolute Abundance (%A) & % Error (E): SB-1 Fungal Spores

Depth	*Ustilago maydis*		*Sphacelotheca reliana*		*Epicoccum nigrum*	
(cm)	%A	E	%A	E	%A	E
0	0.03	0.02	0.00	0.01	0.00	0.00
10	0.01	0.01	0.01	0.01	0.01	0.01
27	0.02	0.03	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00	0.00	0.00
60	0.02	0.01	0.00	0.00	0.00	0.00
63	0.02	0.03	0.00	0.00	0.05	0.05
65	0.00	0.00	0.00	0.00	0.00	0.00
75	0.00	0.00	0.00	0.00	0.00	0.00

Absolute Abundance (%A) & % Error (E): SB-2 Fungal Spores

Depth	*Ustilago maydis*		*Sphacelotheca reliana*		*Epicoccum nigrum*	
(cm)	%A	E	%A	E	%A	E
20	0.05	0.05	0.01	0.02	0.00	0.00
28	0.06	0.04	0.01	0.02	0.00	0.00
36	0.02	0.02	0.00	0.00	0.00	0.00
44	0.00	0.00	0.00	0.00	0.00	0.00
52	0.00	0.00	0.00	0.00	0.00	0.00
57	0.00	0.00	0.00	0.00	0.00	0.00
63	0.03	0.03	0.00	0.00	0.01	0.01
76	0.00	0.00	0.00	0.00	0.00	0.00

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

SB-1 Desmids (Pre-Acetolysis) Raw Data																			
Depth, cm	**Lycopodium**	***C. depressum***	***C. botrytis***	***C. formosulum/ C. reniforme***	***C. protractum***	***C. variolatum/C. subcucumis/ C. subcrenatum***	***C. punctulatum/C. granatum***	***C. pseudopyramidatum/ C. pyramidatum***	***C. franzstonii?***	***Cosmarium spp.***	***S. planctonicum/S. pingue***	***S. chaetoceras***	***S. sebaldi***	***S. punctulatum***	***S.spp***	***E. lacustre/ E. luetkemuelleri***	***E. bidentatum/ E. denticulatum***	***Euastrum spp.***	**Total Desmids**
0	2	11	28	0	7	0	3	0	0	12	13	7	0	0	5	1	3	0	90
2	50	9	10	1	7	0	0	10	9	28	0	2	2	0	10	4	0	1	96
5	2	10	32	13	6	0	2	0	0	24	6	4	1	0	3	0	1	0	102
10	3	11	23	21	16	0	5	0	0	10	21	7	0	0	1	0	2	0	117
15	3	9	11	4	5	0	3	0	0	11	10	3	0	0	5	0	8	0	69
20	14	6	11	0	10	0	8	0	0	7	18	2	0	0	5	0	0	0	67
25	10	8	11	6	2	0	0	41	0	0	0	0	0	0	8	0	0	0	76
27	43	17	7	6	6	0	0	1	2	15	0	0	0	0	4	7	4	10	79
30	6	7	10	12	2	14	2	5	0	0	2	0	11	6	0	0	14	0	85
35	4	3	23	16	2	7	12	18	0	19	0	0	0	0	0	0	4	0	104
40	2	0	2	8	5	0	2	16	0	15	0	0	0	0	0	0	7	0	55
45	6	5	0	2	5	14	4	58	0	37	0	2	0	1	11	2	7	0	148
50	10	4	10	0	14	0	9	60	17	41	0	3	2	3	2	3	23	2	193
55	12	2	0	0	11	2	5	32	12	27	0	2	2	2	4	6	4	0	111
60	20	0	2	0	13	2	7	27	2	22	0	0	0	2	0	9	4	0	111
63	50	7	8	0	3	2	0	13	3	18	0	0	0	0	0	5	1	7	67
65	4	0	2	0	8	2	2	43	0	12	0	0	2	2	0	10	9	0	92
70	10	2	0	0	8	2	7	35	8	27	0	0	0	2	0	0	2	0	93
75	4	0	3	0	1	1	7	20	1	18	0	0	4	1	1	3	3	1	64
80	21	0	0	0	2	0	0	28	0	25	0	0	0	2	0	0	0	0	57

Analyst: Olena Volik (top 45 cm presented in Volik, 2014) and Nicholas Riddick (2, 27 & 63 cm)
Lycopodium Tablet: 10,850 +/-200 spores, 20,848 +/-500 spores for 2, 27 & 63 cm
Volume: 5 mL, 2.5 mL for 2, 27 & 63 cm

Absolute Abundance (%A) & % Error (E): SB-1 Desmids

Depth, cm	*C. depressum*		*C. botrytis*		*C. formosulum/ C. reniforme*		*C. protractum*		*C. variolatum/C. subcucumis/ C. subcrenatum*		*C. punctulatum/C. granatum*		*C. pseudopyramidatum/ C. pyramidatum*		*C. franzonii?*		*S. planctonicum/S. pingue*		*S. chaetoceras*		*S. sebaldi*		*S. punctulatum*		*E. lacustre/ E. hedhemuelleri*		*E. bilenatum/ E. denticulatum*	
	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E
0	0.12	0.07	0.31	0.10	0.00	0.00	0.08	0.06	0.00	0.00	0.03	0.04	0.00	0.00	0.00	0.00	0.14	0.07	0.08	0.06	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.04
2	0.09	0.06	0.10	0.06	0.01	0.02	0.07	0.05	0.00	0.00	0.00	0.00	0.10	0.06	0.09	0.06	0.00	0.00	0.02	0.03	0.02	0.03	0.00	0.00	0.04	0.04	0.00	0.00
5	0.10	0.06	0.31	0.09	0.13	0.06	0.06	0.05	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.06	0.05	0.04	0.04	0.01	0.02	0.00	0.00	0.00	0.00	0.01	0.02
10	0.09	0.05	0.20	0.07	0.18	0.07	0.14	0.06	0.00	0.00	0.04	0.04	0.00	0.00	0.00	0.00	0.18	0.07	0.06	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
15	0.13	0.08	0.16	0.09	0.06	0.06	0.07	0.06	0.00	0.00	0.04	0.05	0.00	0.00	0.00	0.00	0.14	0.08	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.08
20	0.09	0.07	0.16	0.09	0.00	0.00	0.15	0.09	0.00	0.00	0.12	0.08	0.00	0.00	0.00	0.00	0.27	0.11	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.11	0.07	0.14	0.08	0.08	0.06	0.03	0.04	0.00	0.00	0.00	0.00	0.54	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.22	0.09	0.09	0.06	0.08	0.06	0.08	0.06	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.06	0.05	0.05
30	0.08	0.06	0.12	0.07	0.14	0.07	0.02	0.03	0.16	0.08	0.02	0.03	0.06	0.05	0.00	0.00	0.02	0.03	0.00	0.00	0.13	0.07	0.07	0.05	0.00	0.00	0.16	0.08
35	0.03	0.03	0.22	0.08	0.15	0.07	0.02	0.03	0.07	0.05	0.12	0.06	0.17	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04
40	0.00	0.00	0.04	0.05	0.15	0.09	0.09	0.08	0.00	0.00	0.04	0.05	0.29	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.09
45	0.03	0.03	0.00	0.00	0.01	0.02	0.03	0.03	0.09	0.05	0.03	0.03	0.39	0.08	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.01	0.01	0.02	0.05	0.03
50	0.02	0.02	0.05	0.03	0.00	0.00	0.07	0.04	0.00	0.00	0.05	0.03	0.31	0.07	0.09	0.04	0.00	0.00	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.12	0.05
55	0.02	0.02	0.00	0.00	0.00	0.00	0.10	0.06	0.02	0.02	0.05	0.04	0.29	0.08	0.11	0.06	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.04	0.04	0.03
60	0.00	0.00	0.02	0.02	0.00	0.00	0.12	0.06	0.02	0.02	0.06	0.05	0.24	0.08	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.08	0.05	0.04	0.03
63	0.10	0.07	0.12	0.08	0.00	0.00	0.04	0.05	0.03	0.04	0.00	0.00	0.19	0.09	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.06	0.01	0.03
65	0.00	0.00	0.02	0.03	0.00	0.00	0.09	0.06	0.02	0.03	0.02	0.03	0.47	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.02	0.03	0.11	0.06	0.10	0.06
70	0.02	0.03	0.00	0.00	0.00	0.00	0.09	0.06	0.02	0.03	0.08	0.05	0.38	0.10	0.09	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.02	0.03
75	0.00	0.00	0.05	0.05	0.00	0.00	0.02	0.03	0.02	0.03	0.11	0.08	0.31	0.11	0.02	0.03	0.00	0.00	0.00	0.00	0.06	0.06	0.02	0.03	0.05	0.05	0.05	0.05
80	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.00	0.00	0.00	0.00	0.49	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.00	0.00	0.00	0.00

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

SB-1 Desmids (Post-Acetolysis) Raw Data					
Depth	**Lycopodium**	***Cosmarium***	***Staurastrum***	***Euastrum***	**Total Desmids**
0	2	2	0	0	2
5	2	17	6	1	24
10	3	5	4	0	9
15	3	1	0	0	1
25	10	3	0	0	3
30	6	1	0	0	1
35	4	2	0	0	2
40	2	1	0	1	2
45	6	18	0	2	20
50	10	62	17	12	91
55	12	11	0	0	11
65	4	0	0	0	0
70	10	9	0	2	11
75	4	30	4	7	41
80	12	0	0	1	1

Analyst: Nicholas Riddick in 2015
Lycopodium Tablet: 10,850 +/-200 spores
Volume: 5 mL

Notes: Acetolysed SB-1 sample residues. For comparison with the pre-acetolysis desmid assemblage, counts were completed to the same *Lycopodium* count as Volik (2014).

SB-1 Pediastrum Raw Data							
Depth, cm	***Lycopodium***	***P. boryanum var boryanum***	***P. boryanum var pseudoglabrum***	***P. integrum***	***P. duplex duplex***	***P. simplex var simplex***	**Total Pediastrum**
0	20	19	42	0	0	1	62
2	50	6	0	0	0	0	6
5	16	9	47	0	2	2	60
10	23	23	25	0	1	2	51
15	40	22	28	0	0	3	53
20	39	10	49	0	2	1	62
25	50	25	24	0	2	2	53
27	50	1	0	1	0	0	4
30	60	21	26	1	2	2	52
35	30	12	24	5	1	18	60
40	21	8	21	4	0	22	55
45	37	0	25	2	0	28	55
50	50	0	12	2	2	34	50
55	60	0	51	0	0	11	62
60	100	10	21	0	0	21	52
63	50	6	0	1	0	0	12
65	40	0	21	0	0	21	42
70	250	0	0	0	0	51	51
75	200	0	25	0	0	26	51
80	200	0	27	0	0	24	51

Analyst: Olena Volik (top 45 cm presented in Volik, 2014) and Nicholas Riddick (2, 27 & 63 cm)
Lycopodium Tablet: 10,850 +/-200 spores, 20,848 +/-500 spores for 2, 27 & 63 cm
Volume: 5 mL, 2.5 mL for 2, 27 & 63 cm

Absolute Abundance (%A) & % Error (E): SB-1 *Pediastrum*

Depth, cm	*P. boryanum var boryanum*		*P. boryanum var pseudoglabrum*		*P. integrum*		*P. duplex duplex*		*P. simplex var simplex*	
	%A	E	%A	E	%A	E	%A	E	%A	E
0	0.31	0.11	0.68	0.12	0.00	0.00	0.00	0.00	0.02	0.03
2	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.15	0.09	0.78	0.10	0.00	0.00	0.03	0.05	0.03	0.05
10	0.45	0.14	0.49	0.14	0.00	0.00	0.02	0.04	0.04	0.05
15	0.42	0.13	0.53	0.13	0.00	0.00	0.00	0.00	0.06	0.06
20	0.16	0.09	0.79	0.10	0.00	0.00	0.03	0.04	0.02	0.03
25	0.47	0.13	0.45	0.13	0.00	0.00	0.04	0.05	0.04	0.05
27	0.25	0.42	0.00	0.00	0.25	0.42	0.00	0.00	0.00	0.00
30	0.40	0.13	0.50	0.14	0.02	0.04	0.04	0.05	0.04	0.05
35	0.20	0.10	0.40	0.12	0.08	0.07	0.02	0.03	0.30	0.12
40	0.15	0.09	0.38	0.13	0.07	0.07	0.00	0.00	0.40	0.13
45	0.00	0.00	0.45	0.13	0.04	0.05	0.00	0.00	0.51	0.13
50	0.00	0.00	0.24	0.12	0.04	0.05	0.04	0.05	0.68	0.13
55	0.00	0.00	0.82	0.10	0.00	0.00	0.00	0.00	0.18	0.10
60	0.19	0.11	0.40	0.13	0.00	0.00	0.00	0.00	0.40	0.13
63	0.50	0.28	0.00	0.00	0.08	0.16	0.00	0.00	0.00	0.00
65	0.00	0.00	0.50	0.15	0.00	0.00	0.00	0.00	0.50	0.15
70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
75	0.00	0.00	0.49	0.14	0.00	0.00	0.00	0.00	0.51	0.14
80	0.00	0.00	0.53	0.14	0.00	0.00	0.00	0.00	0.47	0.14

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

SB-1 Thecamoebians Raw Data															
Depth, cm	***Cucurbitella tricuspis***	***Difflugia obolonga "obolonga"***	***D. obolonga "glans"***	***D. obolonga "tenuis"***	***D. obolonga "linearis"***	***D. protaeiformis***	***D. corona***	***D. urens***	***D. urceolata***	***Pontigulasia compressa***	***C. constricta "aerophila"***	***C. constricta***	***C. aculeata***	***Lesquerusia spiralis***	***Total thecamoebian***
0	0	89	7	2	0	1	1	0	0	41	6	13	21	1	182
5	1	72	3	6	1	0	0	0	0	38	8	15	18	0	162
10	1	54	12	11	0	0	1	0	1	40	9	18	19	0	166
15	0	22	5	0	0	6	4	0	0	41	11	21	16	1	127
20	0	81	5	2	0	1	1	0	1	37	5	18	11	0	162
25	0	47	2	7	0	1	1	0	1	31	15	39	21	0	165
30	0	34	1	3	0	1	1	0	2	21	12	43	38	0	156
35	0	28	2	0	1	1	0	0	1	23	8	48	41	0	153
40	0	25	1	2	1	0	1	1	0	24	7	68	35	0	165
45	0	21	7	1	0	0	0	1	1	7	12	54	60	0	164
50	0	11	1	1	1	2	1	0	0	5	21	65	59	1	168
55	0	10	4	4	0	0	0	0	0	12	32	54	67	2	185
60	0	6	0	1	0	0	1	0	0	3	21	58	65	0	155
65	0	8	6	1	0	1	0	0	0	3	12	62	57	1	151
70	0	8	1	0	0	0	0	0	0	3	10	71	59	0	152
75	0	7	0	0	0	0	0	0	0	1	12	68	72	0	160
80	0	11	0	0	0	0	0	0	0	1	23	65	69	0	169

Analyst: Olena Volik (top 45 cm presented in Volik, 2014)
Volume: 5 mL

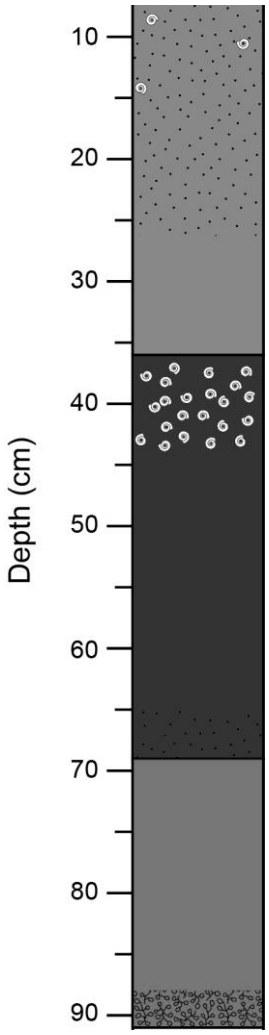
Absolute Abundance (%A) & % Error (E): SB-1 Thecamoebians

Depth, cm	*Cucubitella tricuspis*		*Difflugia oblonga "oblonga"*		*D. oblonga "glans"*		*D. oblonga "tenuis"*		*D. oblonga "linearis"*		*D. pyriformis*		*D. corona*		*D. urens*		*D. urceolata*		*Fontigulasia compressa*		*C. constricta "aerophila"*		*C. constricta*		*C. aculeata*		*Lesquereusia spiralis*	
	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E	%A	E
0	0.00	0.00	0.49	0.07	0.04	0.03	0.01	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.23	0.06	0.03	0.03	0.07	0.04	0.12	0.05	0.01	0.01
5	0.01	0.01	0.44	0.08	0.02	0.02	0.04	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.07	0.05	0.03	0.09	0.04	0.11	0.05	0.00	0.00
10	0.01	0.01	0.33	0.07	0.07	0.04	0.07	0.04	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.24	0.07	0.05	0.03	0.11	0.05	0.11	0.05	0.00	0.00
15	0.00	0.00	0.17	0.07	0.04	0.03	0.00	0.00	0.00	0.00	0.05	0.04	0.03	0.03	0.00	0.00	0.00	0.00	0.32	0.08	0.09	0.05	0.17	0.06	0.13	0.06	0.01	0.02
20	0.00	0.00	0.50	0.08	0.03	0.03	0.01	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.23	0.06	0.03	0.03	0.11	0.05	0.07	0.04	0.00	0.00
25	0.00	0.00	0.28	0.07	0.01	0.02	0.04	0.03	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.19	0.06	0.09	0.04	0.24	0.06	0.13	0.05	0.00	0.00
30	0.00	0.00	0.22	0.06	0.01	0.01	0.02	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.02	0.13	0.05	0.08	0.04	0.28	0.07	0.24	0.07	0.00	0.00
35	0.00	0.00	0.18	0.06	0.01	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.15	0.06	0.05	0.04	0.31	0.07	0.27	0.07	0.00	0.00
40	0.00	0.00	0.15	0.05	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.15	0.05	0.04	0.03	0.41	0.08	0.21	0.06	0.00	0.00
45	0.00	0.00	0.13	0.05	0.04	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.04	0.03	0.07	0.04	0.33	0.07	0.37	0.07	0.00	0.00
50	0.00	0.00	0.07	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.03	0.03	0.13	0.05	0.39	0.07	0.35	0.07	0.01	0.01
55	0.00	0.00	0.05	0.03	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.17	0.05	0.29	0.07	0.36	0.07	0.01	0.01
60	0.00	0.00	0.04	0.03	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02	0.02	0.14	0.05	0.37	0.08	0.42	0.08	0.00	0.00
65	0.00	0.00	0.05	0.04	0.04	0.03	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.08	0.04	0.41	0.08	0.38	0.08	0.01	0.01
70	0.00	0.00	0.05	0.04	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.07	0.04	0.47	0.08	0.39	0.08	0.00	0.00
75	0.00	0.00	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.08	0.04	0.43	0.08	0.45	0.08	0.00	0.00
80	0.00	0.00	0.07	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.14	0.05	0.38	0.07	0.41	0.07	0.00	0.00

% Error = 1.96 * (SQRT(((Absolute Abundance *(1- Absolute Abundance))/Total)))

Patterson RT & Fishbein E (1989). Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology 63(02): 245-248

Appendix B: SB-2 Core Description & Nutrient and Heavy Metal Lab Results



	Colour	*Cohesiveness*	*Notes*
	Buff (0cm - 7cm)	Low (0cm - 7cm)	N/A
	Grey/Brown (7cm - 36cm)	Low (7cm - 28cm)	Moderate Shell Content (7cm - 16cm)
			N/A
		Medium (28cm - 36cm)	
	Reddish (36cm - 69cm)	High (36cm - 91cm)	High Shell Content (36cm - 46cm)
			N/A
	Brown (69cm - 91cm)		
			Fibrous Plant Material (88cm - 91cm)

In the bottom 30 cm of SB-2, the core is cohesive and brown in colour, with fibrous plant material between 88 and 91 cm. The colour changes at 69 cm (reddish) and is consistent until the ragweed rise (~40 cm), around which there is high shell content (between 36-46 cm). After the ragweed rise, at 36 cm, the colour changes to grey-brown and the core loses cohesion. Between 7-16 cm, there is another zone of moderate shell content and at 7 cm the colour changes again (buff). Changes in the core, particularly after the ragweed rise, can likely be attributed to human activities in the watershed.

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Work Order No.:2518834
Received : 2014-05-05
PO Number:
Reported: 2014-05-15
Project Name: Lake Simcoe/Smith's Bay
Chain of Custody No.: 26502

Client Sample ID	Sample Date	Lab ID	Parameter	Result	Unit	RDL	Date Analyzed	Method
0 cm	2014-04-29	**366627**	Arsenic	1.07	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	5.06	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	1.04	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	6.59	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	10.7	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	4.7	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0157	mg/Kg	0.0157	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	1.57	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	266	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	35.5	mg/Kg	2.00	2014-05-07	EPA 3050B
10 cm	2014-04-29	**366628**	Arsenic	1.40	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	5.80	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	1.21	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	6.71	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	12.2	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	0.32	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	5.3	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.011	mg/Kg	0.011	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.95	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	159	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	30.1	mg/Kg	2.00	2014-05-07	EPA 3050B
20 cm	2014-04-29	**366629**	Arsenic	1.40	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	5.57	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	1.23	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	6.37	mg/Kg	2.00	2014-05-07	EPA 3050B

Reported by:

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Work Order No.:2518834
Received : 2014-05-05
PO Number:
Reported: 2014-05-15
Project Name: Lake Simcoe/Smith's Bay
Chain of Custody No.: 26502

Client Sample ID	Sample Date	Lab ID	Parameter	Result	Unit	RDL	Date Analyzed	Method
20 cm	2014-04-29	**366629**	Lead	11.2	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	0.32	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	5.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0115	mg/Kg	0.0115	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.84	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	166	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	28.8	mg/Kg	2.00	2014-05-07	EPA 3050B
30 cm	2014-04-29	**366630**	Arsenic	1.20	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	5.41	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	1.37	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	5.98	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	8.29	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	4.3	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0118	mg/Kg	0.0118	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	1.06	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	210	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	23.7	mg/Kg	2.00	2014-05-07	EPA 3050B
40 cm	2014-04-29	**366631**	Arsenic	<1.00	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	5.32	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	1.77	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	3.84	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	0.41	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	3.1	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0087	mg/Kg	0.0087	2014-05-12	APHA 4500/HACH 8503m

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Project Name: Lake Simcoe/Smith's Bay
Chain of Custody No.: 26502

Client Sample ID	Sample Date	Lab ID	Parameter	Result	Unit	RDL	Date Analyzed	Method
40 cm	2014-04-29	**366631**	NO3 (Nitrate)	0.31	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	167	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	12.4	mg/Kg	2.00	2014-05-07	EPA 3050B
50 cm	2014-04-29	**366632**	Arsenic	<1.00	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	8.53	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	2.64	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	4.62	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	<0.40	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	4.7	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0089	mg/Kg	0.0089	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.49	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	149	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	17.4	mg/Kg	2.00	2014-05-07	EPA 3050B
60 cm	2014-04-29	**366633**	Arsenic	<1.00	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	9.37	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	2.98	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	5.49	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	1.78	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	5.3	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0091	mg/Kg	0.0091	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.79	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	197	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	21.0	mg/Kg	2.00	2014-05-07	EPA 3050B

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Client Sample ID	Sample Date	Lab ID	Parameter	Result	Unit	RDL	Date Analyzed	Method
70 cm	2014-04-29	**366634**	Arsenic	<1.00	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	6.00	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	1.97	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	2.71	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	<0.40	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	3.2	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0072	mg/Kg	0.0072	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.49	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	143	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	11.8	mg/Kg	2.00	2014-05-07	EPA 3050B
80 cm	2014-04-29	**366635**	Arsenic	<1.00	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	6.98	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	2.28	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	4.00	mg/Kg	2.00	2014-05-07	EPA 3050B
			Lead	<0.40	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	4.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0075	mg/Kg	0.0075	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.68	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	146	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	15.4	mg/Kg	2.00	2014-05-07	EPA 3050B
90 cm	2014-04-29	**366636**	Arsenic	<1.00	mg/Kg	1.00	2014-05-07	Hydr/Vap Gen EPA3005
			Cadmium	<0.50	mg/Kg	0.50	2014-05-07	EPA 3050B
			Chromium	6.83	mg/Kg	0.30	2014-05-07	EPA 3050B
			Cobalt	2.21	mg/Kg	0.30	2014-05-07	EPA 3050B
			Copper	4.36	mg/Kg	2.00	2014-05-07	EPA 3050B

Reported by:

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CERTIFICATE OF ANALYSIS

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Work Order No.:2518834
Received : 2014-05-05
PO Number:
Reported: 2014-05-15
Project Name: Lake Simcoe/Smith's Bay
Chain of Custody No.: 26502

Client Sample ID	Sample Date	Lab ID	Parameter	Result	Unit	RDL	Date Analyzed	Method
90 cm	2014-04-29	**366636**	Lead	<0.40	mg/Kg	0.40	2014-05-07	EPA 3050B
			Mercury	<0.15	mg/Kg	0.15	2014-05-07	Hydr/Vap Gen EPA3005
			Molybdenum	<0.30	mg/Kg	0.30	2014-05-07	EPA 3050B
			Nickel	4.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			NO2 (Nitrite)	<0.0068	mg/Kg	0.0068	2014-05-12	APHA 4500/HACH 8503m
			NO3 (Nitrate)	0.68	mg/Kg	0.04	2014-05-12	APHA 4500/HACH 8171m
			Selenium	<1.0	mg/Kg	1.0	2014-05-07	EPA 3050B
			TP	134	mg/Kg	0.02	2014-05-09	APHA 4500
			Zinc	16.5	mg/Kg	2.00	2014-05-07	EPA 3050B

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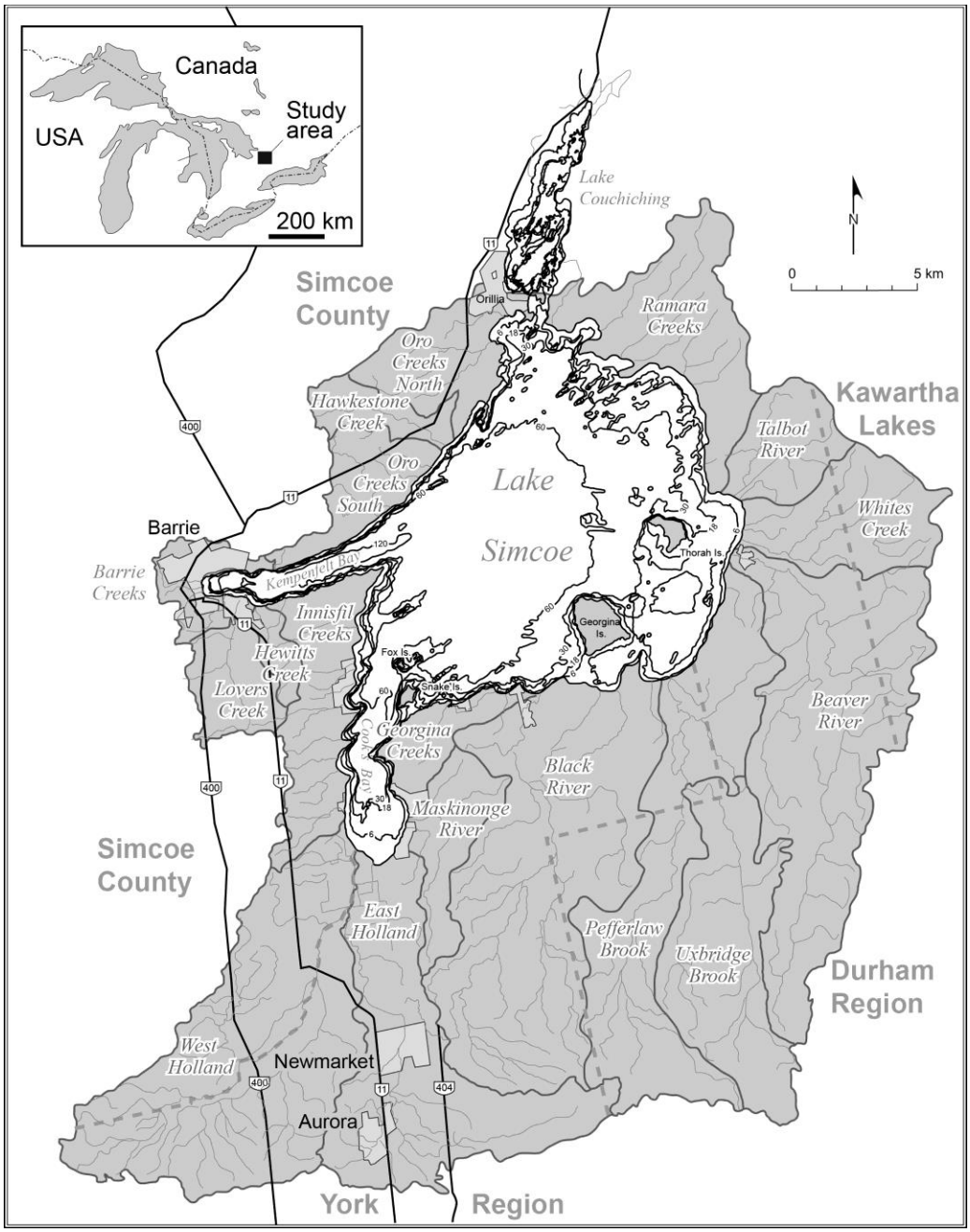
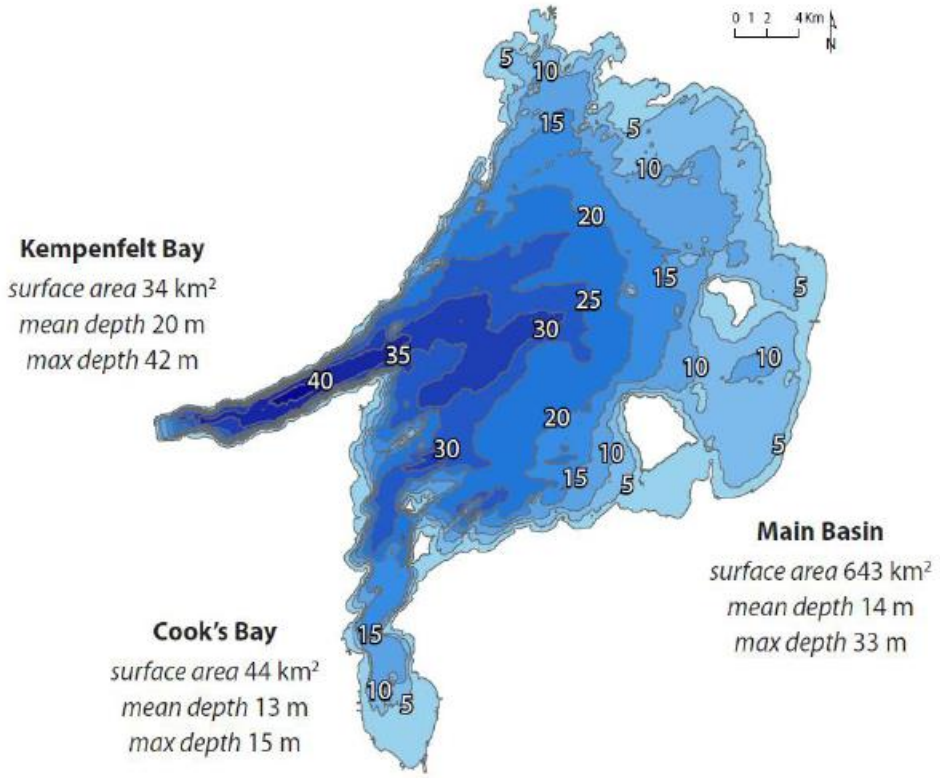
Appendix C: Lake Simcoe Bathymetry & Circulation Models

Source: Danesh DC, McCarthy FMG, Volik O & Drljepan M (2013). Non-pollen palynomorphs as indicators of water quality in Lake Simcoe, Ontario, Canada. Palynology 37: 231-245

Ontario Ministry of the Environment (2010). ON (Canada): Queen's Printer for Ontario; Available from: http://www.ene.gov.on.ca/environment/en/local/lake_simcoe_protection/index.htm



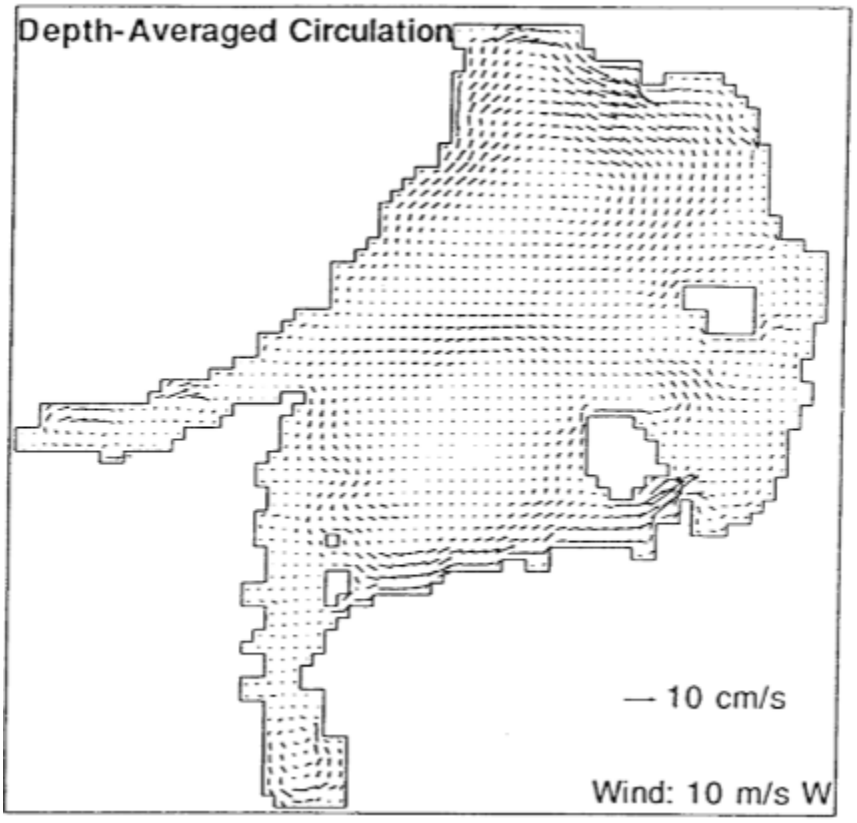
Source: Young JD, Landre AL, Winter JG, Jarjanazi H, Kingston J (2010) Lake Simcoe water quality update Ontario Ministry of the Environment Report Available at: http://www.enegovonca/stdprodconsume/groups/lr/@ene/@resources/documents/resource/ stdprod_081603pdf

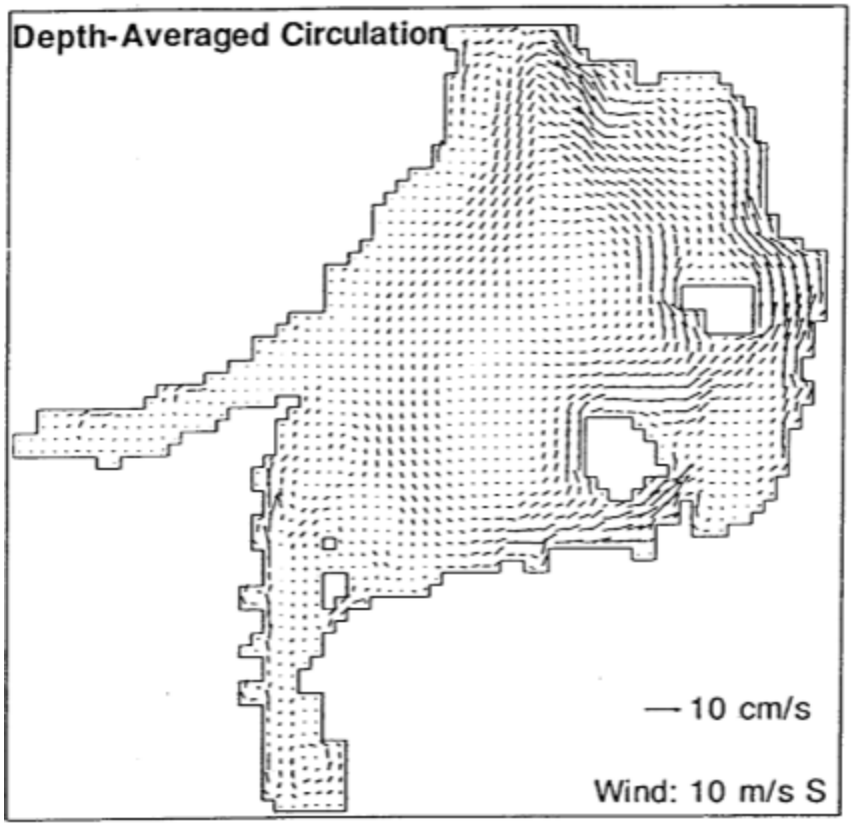


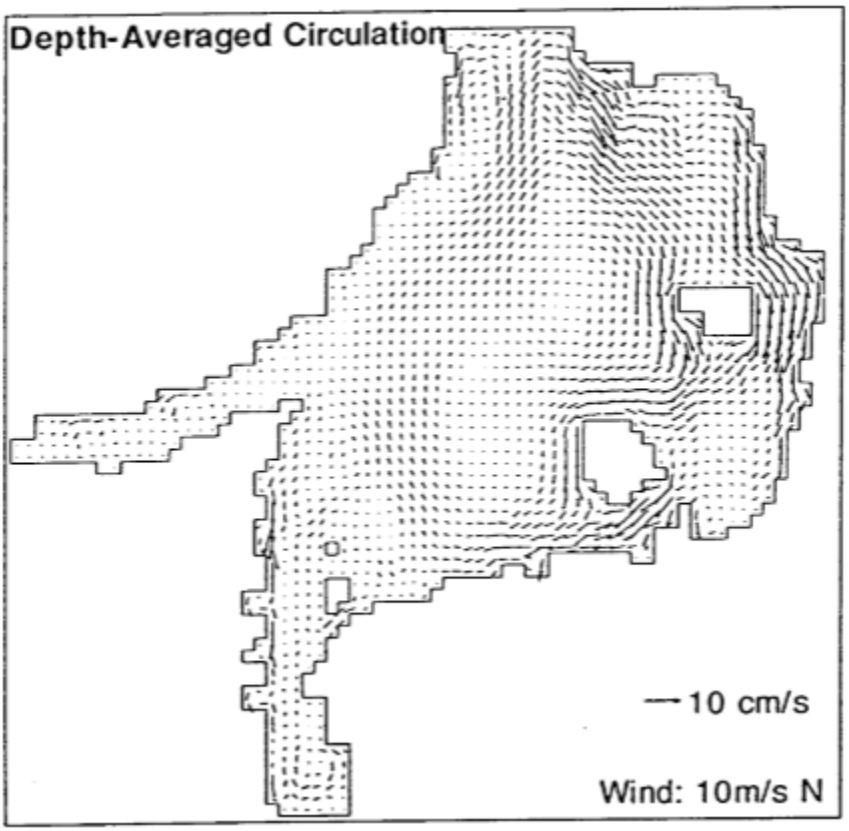
Bathymetry information derived by the OMNR from Canadian Hydrographic Service original depth sounding field sheet, 1957, scale 1:36,000. This map should not be relied on as a precise indicator of routes or locations, nor as a guide to navigation. The OMNR shall not be liable in any way for the use of, or reliance upon, this map or any information on this map.

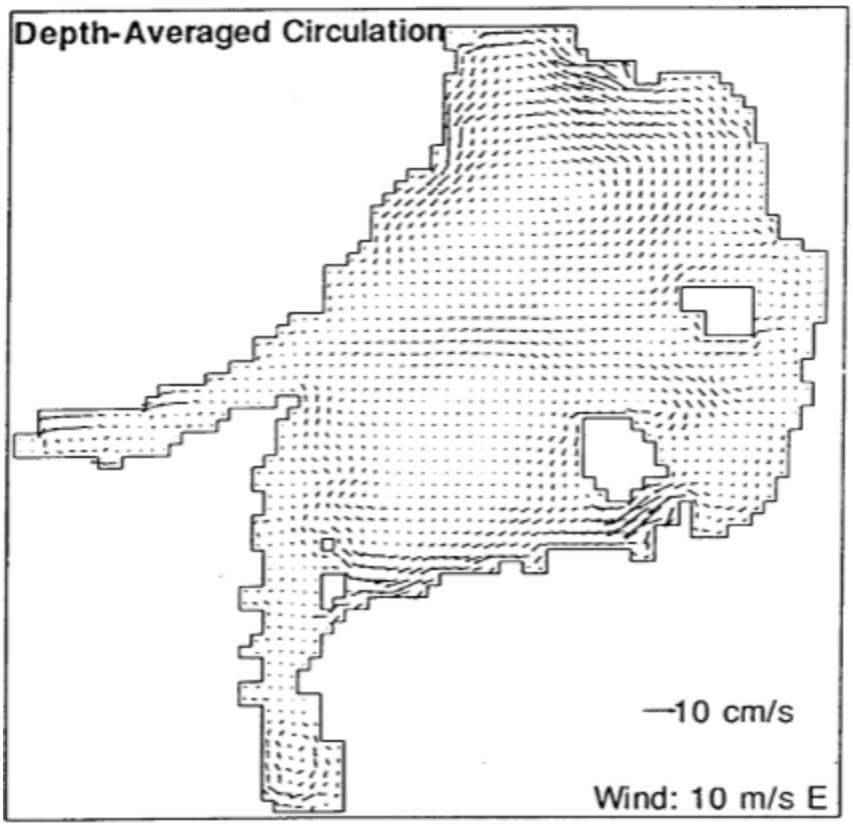
Source: Hydroflux Engineering (1992). Hydrodynamic Computer Model of Major Water Movement Patterns in Lake Simcoe. Prepared for LSEMS.

Circulation models were useful when considering transport and deposition within the lake. Based on these models (accounting for primary wind directions) deposition is likely to occur in the north and east, which corresponds with high biomass concentrations (measure of productivity).




Depth-Averaged Circulation
10 cm/s
Wind: 10 m/s S

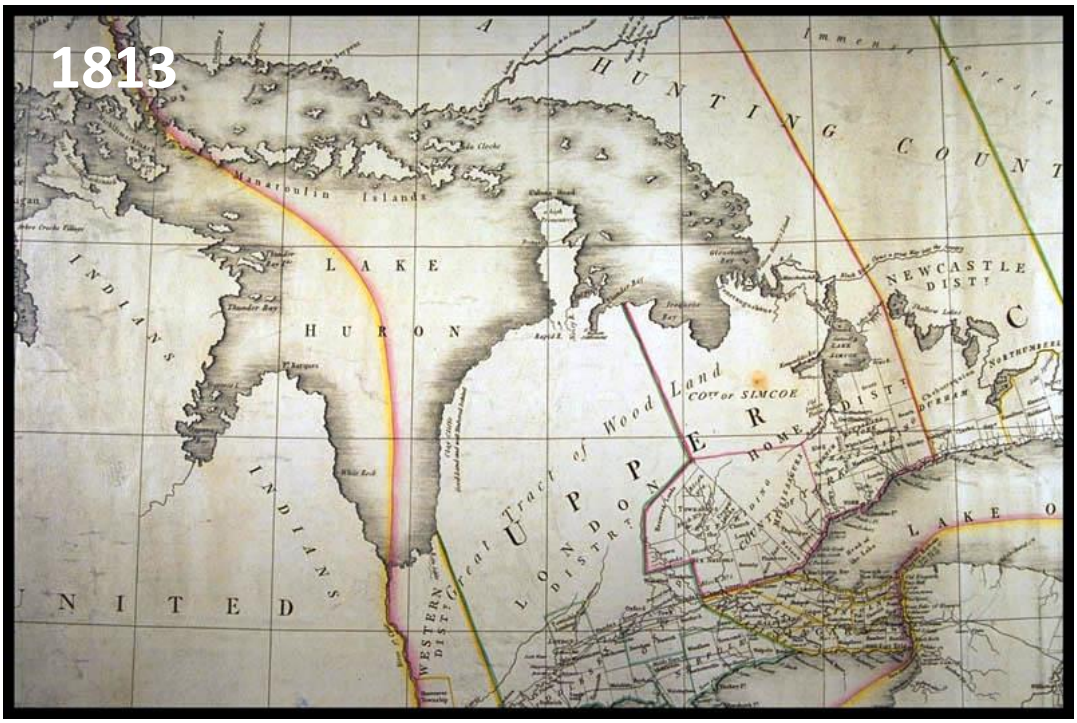

Depth-Averaged Circulation
10 cm/s
Wind: 10m/s N


Depth-Averaged Circulation
10 cm/s
Wind: 10 m/s E

Appendix D: Upper Canada Historical Maps

Source: McMaster University Library. A Map of the Province of Upper Canada. https://library.mcmaster.ca/maps/hmaps.htm#107415

Map produced by David William Smyth and published by William Faden (1750-1836) in 1813.



Source: McMaster University Library. A Map of the Province of Upper Canada. https://library.mcmaster.ca/maps/hmaps.htm#107415

Map published by James Wyld (1812-1887) in 1845.